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DESIGN, FABRICATION, AND TESTS OF TUBULAR BERYLLIUM AND Be-38Al ALLOY TRUSS-TYPE STRUCTURES

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SUMMARY

Four lightly loaded, tubular, truss-type structures with the same configuration have been designed, fabricated, and tested. Adhesively bonded joints were used to fabricate a beryllium truss, a Be-38Al alloy truss, and an aluminum truss. The fourth truss was aluminum with welded joints. The bonded trusses were designed for the same loading condition. The beryllium and Be-38Al trusses had a mass of 1.42 and 1.51 lbm (0.64 and 0.68 kg), respectively, whereas the bonded aluminum truss had a mass of 3.0 lbm (1.36 kg).

The trusses were subjected to both dynamic and static tests. The trusses successfully survived the dynamic tests which subjected the trusses to the maximum design loading conditions. For the dynamic tests, comparisons between measured and calculated first-bending-mode frequencies and mode shapes also show satisfactory agreement. All four trusses exhibited a nonlinear response to dynamic loads. For the static tests, comparisons between measured and calculated truss member strains and joint deflections show satisfactory agreement. Viscoelastic joint deflections were observed during static tests on all the bonded trusses. Joint failures observed during static tests on the bonded aluminum truss were attributed to the viscoelastic properties of the adhesive.

INTRODUCTION

Beryllium and Be-Al alloys are attractive for structural applications because of their high stiffness and low density. In spite of these advantages, the structural application of these materials is not widespread. This limited use is due, in part, to the brittle behavior of beryllium under biaxial stresses. Most current applications use beryllium and/or Be-38Al in sheet form (see, for example, refs. 1 to 3) and little attention has been given to these materials as tubular members in a load-carrying structure. However, the use of beryllium or Be-38Al alloy in truss-type structures appears promising since truss-type configurations offer the possibility of uniaxially loading the tubular truss members. In addition, truss networks are often designed by elastic stability considerations, which make materials with high stiffness particularly attractive.

Because of the interest in lightweight tubular spacecraft structures and because of the limited amount of information available on beryllium and Be-38Al tubing, an investigation to determine the applicability of thin-wall beryllium and Be-38Al tubing for lightly loaded truss-type structures was initiated. The first two phases of this investigation (refs. 4 and 5) were concerned with the mechanical properties and column behavior of thin-wall beryllium and Be-38Al tubing.

The study reported herein, the final phase of the investigation, describes the design and fabrication of a beryllium truss and a Be-38Al truss. To provide a basis for comparison, the design and fabrication of two aluminum trusses are also described. The present paper also presents a detailed description of the structural response of the four trusses to both dynamic and static loading conditions. The configuration and joint-location coordinates for the trusses are shown in figure 1. This figure also shows the directional reference axes used herein.

SYMBOLS

The units used for physical quantities defined in this paper are given both in the U.S. Customary Units and in the International System of Units (SI). (See ref. 6.) Conversion factors pertinent to the present investigation are presented in appendix A.

A	area, inches^2 (meters^2)
C	constant
d_1,d_2	maximum diameters, inches (meters) (see fig. 2)
D	mean diameter, inches (meters)
E	modulus of elasticity, pounds force/inch^2 (newtons/meter^2)
f	frequency, hertz
g	gravity units
h_1,h_2,h_3,h_4	heights, inches (meters) (see fig. 2)
K	empirical correction term
L	column length, inches (meters)

m	mass, pounds mass (kilograms)
m_1, m_2, m_3, m_4	masses, pounds mass (kilograms) (see fig. 2)
P	concentrated load, pounds force (newtons)
P_{cr}	column buckling load, pounds force (newtons)
t	wall thickness, inches (meters)
T	test temperature, ^{O}F (^{O}K)
T_o	reference temperature, ^{O}F (^{O}K)
X_1, X_2, X_1X_2, X_3	truss directional references (see fig. 1), inches (meters)
δ	deflection, inches (meters)
δ_{10}	deflection at joint 10, inches (meters)
ϵ	strain
$\epsilon_1, \epsilon_2, \epsilon_3$	measured longitudinal truss member strains
ρ	density, pounds mass/inch^3 (kilograms/meter^3)
σ	stress, pounds force/inch^2 (newtons/meter^2)
φ	location of neutral axis of bending with respect to ϵ_1, degrees

Subscripts:

a	axial
Al	aluminum
av	average
b	induced bending

Be	beryllium
calc	calculated
exp	experimental
i	integer
max	maximum
y	yield

TRUSSES

Design Criteria and Configuration Selection

After a review of several unmanned spacecraft designs, the configurational restraints and simulated experimental package masses associated with launch conditions shown in figure 2 were selected for the truss design. The truss design criteria also included the following:

(1) The maximum deflection of the structure at any point must be less than 1 inch (25 mm).

(2) The first-mode resonant frequency of the truss must be greater than 30 hertz.

(3) All vertical truss members in a given tier must have the same section properties.

(4) Minimum diameter and wall thickness for truss members are 0.25 and 0.020 inch (6.4 and 0.51 mm), respectively.

(5) The diameters of truss members shall be restricted to those considered standard for aluminum tubing.

The design loads included static forces equivalent to a 10g longitudinal acceleration and dynamic forces induced by a 2g-peak lateral acceleration from 10 to 500 hertz input at the base of the truss. Although the design criteria selected are arbitrary, they are, nevertheless, considered typical of the major restraints which would be associated with this type of structure.

To select a representative truss-type structure, a variety of truss configurations conforming to the design criteria were analyzed with the aid of a digital-computer program (ref. 7). Both aluminum and beryllium trusses were analyzed. The more efficient configurations analyzed included three- and four-legged trusses with 21 to 29 members

and with 10 to 13 joints. During the configuration selection studies, the truss members were assumed to be pinned-end columns and an amplification factor (transmissibility) of 20 was assumed for the 2g-peak lateral acceleration. The trusses were analyzed and sized for both the experimental-package masses shown in figure 2 and for a single 5.0-lbm (2.3-kg) simulated experimental package at the top of the truss; these two loading configurations will be referred to as the multiple-mass and single-mass loading conditions, respectively.

The results of the configuration selection studies indicated that the dynamic loads governed the design. The dynamic loads were such that most of the truss members were lightly loaded and were sized by elastic column stability considerations; consequently, stresses were low.

Based on the results of the configuration and preliminary member-sizing studies, the truss configuration shown in figure 1 was selected as the test model configuration. A detailed discussion of the configuration studies is presented in appendix B. This appendix also presents some materials comparison relationships for truss-type structures.

Joints

In addition to indicating a potential mass reduction by substituting beryllium for aluminum truss members, the configuration studies also showed that joint mass could represent a large percentage of total truss mass, particularly for trusses with beryllium truss members. Several mechanically fastened and adhesively bonded joint designs were analyzed for both mass and ease of fabrication. The joint design selected is shown in figure 3. This joint design utilizes an electron-beam-welded tubular-aluminum joint cluster to establish the joint geometry. The truss members are attached to the joint cluster with adhesively bonded, two-piece split aluminum collars. In addition to having a low mass, this joint design does not require any fabrication procedures that are not well established, such as welding beryllium or Be-38Al tubing. It also minimizes the possibility of developing large fabrication-induced stresses that often occur in mechanically fastened joints which incorporate high-stiffness materials such as beryllium. The two-piece split collars avoid the adhesive distribution problems associated with bonded telescoping joints. Some of the collars were stepped, on the inside diameter, to accommodate differences in truss member and joint tubing diameters.

A paste-type, room-temperature-curing, modified epoxy adhesive was selected for the bonded trusses after a series of bonding studies. These studies, concurrent with the joint design studies, indicated that the selected adhesive should (1) be a room-temperature-curing type to minimize fabrication-induced stresses and fabrication fixture complexity, (2) have high tack and viscosity to ease collar placement and clamping problems, (3) have a shear strength that was relatively insensitive to bond-line thickness

variations to avoid machining of the tubular truss members, and (4) have some flexibility combined with a moderate shear strength to resist the vibratory loads imposed on the truss members.

By utilizing the joint design shown in figure 3, a beryllium truss, a Be-38Al truss, and an aluminum truss were fabricated. A fourth truss was fabricated from aluminum with welded joints. The bonded trusses were sized for the multiple-mass loading condition and the welded aluminum truss was sized for the single-mass loading condition. The as-fabricated bonded beryllium truss is shown in figure 4. Details of the fabrication and assembly procedures used for the bonded trusses are presented in appendix C.

Mass Summary of Fabricated Trusses

The welded aluminum truss was sized for the single-mass loading condition and had a mass of 2.5 lbm (1.14 kg). The component masses and total masses of the bonded trusses are summarized in table I. These trusses were sized for the multiple-mass loading condition. Both the Be-38Al and beryllium trusses are substantially lighter (50 and 53 percent, respectively) than the bonded aluminum truss. A larger difference in mass between the Be-38Al and beryllium trusses was initially expected. The small difference actually found is, in part, the result of being able to utilize standard-diameter tubing more efficiently in the Be-38Al truss than in the beryllium truss. Also, the beryllium truss members were, on the average, 16 percent heavier than had been predicted by using the nominal dimensions of the tubing. This increase in mass was primarily due to thicker than nominal tubing walls. The aluminum and Be-38Al were heavier than predicted by 4 percent and 1 percent, respectively.

The joint mass fractions for the bonded aluminum and beryllium trusses were 17 and 35 percent, respectively. These joint mass fractions are significantly smaller than those estimated for mechanically joined trusses during the configuration studies (appendix B).

The total joint masses for the bonded trusses were approximately equal (table I). The joint clusters in the Be-38Al and beryllium trusses utilized smaller diameter tubing and were somewhat lighter than the aluminum truss. This mass advantage was offset by the increased mass of stepped collars which were used on some joints of the Be-38Al and beryllium trusses.

EXPERIMENTAL TEST PROCEDURE

The three bonded trusses and the welded aluminum truss fabricated during the present investigation were tested under both dynamic and static loading conditions. For all trusses, the dynamic tests were completed before static testing was begun.

For vibration tests, the trusses were mounted on an air-supported slider plate (fig. 5). The bottom of the slider plate had been machined to form a plenum chamber for pressurized air which was introduced through the top of the oil table. An oil film was used to minimize air losses around the edges of the slider plate. Forced vibration excitation was introduced to the slider plate by means of a servocontrolled 10 000-lbf (44-kN) electromagnetic shaker. The trusses were excited laterally in the X_1-, X_2-, and X_1X_2-directions. A typical schedule for the truss-vibration test is presented in table II. The bonded aluminum truss shown in figure 5 is mounted for tests in the X_1X_2-direction. This figure also shows the masses which were attached to the trusses at joints 6, 8, and 9 during the multiple-mass loading-condition tests. These masses were 10, 5, and 5 lbm (4.5, 2.3, and 2.3 kg), respectively. The mass of joint 10 was 5 lbm (2.3 kg) on all trusses.

An accelerometer located in the center of the slider plate was used to control the input excitation level. The input acceleration levels were measured at the control point and also at each of the footpads. Accelerometers were bonded to joints 4, 5, and 7 to measure joint response parallel and perpendicular to the direction of excitation. The response of joint 10 was measured with three accelerometers in the X_1-, X_2-, and X_1X_2-directions.

The electrical outputs of the accelerometers were recorded on oscillographs. In order to measure truss member response, the electrical output of the strain gages was also recorded on oscillographs during the vibration tests. Both the accelerometer response data and the dynamic strain measurements are considered to be accurate to within 5 percent.

For the static tests, the trusses were cantilevered from a rigid base. The test loads were applied at joint 10 in the X_1-, $-X_2$-, and X_1X_2-directions. (See fig. 1.) A manually controlled hydraulic jack loaded the trusses through a cable-and-clevis system so as to minimize the effects of any misalinement between the jack and joint 10. A load cell was rigidly attached to the jack to monitor the test load. Because of the viscoelastic response of the bonded trusses (see appendix D), application of the full test load was usually accomplished within 30 seconds and was usually maintained for 5 minutes. After the load was released, the truss was allowed to recover until the tip (joint 10) deflection returned to zero.

Static joint deflections in the direction of load application were measured by dial gages mounted to a steel frame which was cantilevered from the same rigid base as the truss. Twenty-one strain gages bonded to representative truss members were used to measure member strains. Three foil-type gages were bonded to the center of each selected truss member. The gages were alined in the longitudinal direction and were located at 90° intervals about the circumference. They were used to measure ϵ_1, ϵ_2, and ϵ_3 from which both the axial and the bending strains were calculated. The electrical

outputs of the strain gages were recorded on punched cards by means of an analog-to-digital data-acquisition system. The strain measurements were reproducible to within 5μin./in. (5μm/m) and are considered to be accurate to within 3 percent.

RESULTS AND DISCUSSION OF TRUSS TESTS

The trusses were subjected to both dynamic and static tests. All trusses successfully survived the maximum dynamic loading conditions. These conditions (2g-peak lateral acceleration from 10 to 500 hertz input at the base of the truss) had controlled the design of all truss members. The static tests, experimentally more tractable than the dynamic tests, were performed to provide a detailed comparison of calculated and experimental truss joint deflections and member strains.

Dynamic Tests

A preliminary analysis of the dynamic-test results indicated that excitation in the X_1X_2-direction produced the maximum response for all trusses. This preliminary examination also indicated that the responses of the trusses when excited in either the X_1- or X_2-direction probably included truss—slider-plate interactions and modal coupling. Characterization of these interactions would have required additional vibration testing of the trusses. Because it was considered beyond the scope of the present investigation to characterize completely the vibrational response of the trusses and because in all cases maximum truss response occurred during the X_1X_2-direction vibration tests, only the results of the X_1X_2-direction tests are presented herein.

The major response frequencies and response levels of representative joints to 1g-peak excitation in the X_1X_2-direction are shown in figure 6 for both the single-mass and multiple-mass loading conditions. The lowest response frequencies of the trusses for a 1g-peak input (fig. 6) were in satisfactory agreement with the calculated frequency for the first bending mode (table III). The lowest response frequency of the welded aluminum truss was the only one which was lowered by increased (2g-peak) input excitation. The first-bending-mode frequency of the Be-38Al and beryllium trusses is 1.18 and 1.35 times that of the bonded aluminum truss (table III). This beneficial increase in first-mode frequency is due to the greater stiffness of the Be-38Al and beryllium trusses.

During the single-mass loading condition tests, the response level of joint 10 for the aluminum and Be-38Al trusses exceeded the assumed amplification factor of 20 (fig. 6(a)) for the first-bending mode resonance. The results of the multiple-mass loading condition tests (fig. 6(b)), however, show that the assumed joint-10 amplification factor of 20 at the first-mode resonance was exceeded by only the bonded aluminum truss. Although it was not sized for the 2g-peak multiple-mass loading condition, the welded aluminum truss was

subjected to the 2g-peak sweep test in the multiple-mass loading condition because its response to the 1g-peak sweep test indicated that it would survive. No evidence of damage was observed on any of the bonded trusses or on the welded aluminum truss after the 2g-peak tests in the multiple-mass loading condition.

The nonlinear responses of the trusses to increasing levels of excitation at their lowest resonant frequencies are shown in figure 7. The nonlinear response (softening) of the trusses did not appear to be related to the method of joining. There was some evidence, however, that the maximum response of the bonded trusses was inversely related to their static stiffnesses; i.e., the static stiffness of aluminum truss was the lowest but its response the highest and the stiffness of the beryllium truss the highest with its response the lowest. The first-bending mode shapes of the trusses in both the single-mass and multiple-mass loading conditions (fig. 8) were in reasonable agreement with the calculated mode shapes. The agreement in mode shape for the tests with the multiple-mass loading condition (fig. 8(b)) also indicates that the nonlinear responses shown in figure 7 were characteristic of the whole truss rather than joint 10 or any single truss tier.

The maximum member strains measured during the vibration testing are listed in table IV. The maximum member strains all occurred at the first-mode resonant frequency in the X_1X_2-direction. Maximum strains occurred during the 2g-peak sweep in the multiple-mass loading condition. The strains in table IV are presented as absolute values since no attempt was made to differentiate single vibration cycles during the sweep tests. Examination of a single vibration cycle from dwell-test strain records indicated that the senses (tension or compression) of member strains were properly related to each other and that all strains measured on a single member had the same sense.

The experimental bending strains were derived from the measured strain data by using the equations developed in appendix E. The uncertainty of strains measured with gages later found to be partially debonded precluded the calculation of ϵ_a and ϵ_{max} on some truss members. On the other members, the values of ϵ_a and ϵ_{max} were below the maximum anticipated for a joint-10 amplification factor of 20 during the 2g-peak sweep test. Although the member strains were less than anticipated, it is interesting to note that for the bonded trusses the maximum bending-strain percentages $\frac{\epsilon_b}{\epsilon_a}(100)$ observed during the dynamic tests were approximately 20. This suggests that the dynamic loading condition did not induce any large secondary loads in the truss members.

Static Tests

Joint deflections.- In preliminary static tests the response of the bonded aluminum truss to incrementally applied loads was nonlinear. This nonlinear response was due to the viscoelastic behavior of the adhesive. It was considered beyond the scope of the

present investigation to characterize completely the viscoelastic behavior of the bonded trusses. Therefore, a cursory study was performed to establish the time and temperature dependence of joint deflection to permit a comparison between calculated and experimental joint deflections. The results of the viscoelastic studies and the method used to correct the experimental truss deflections for temperature effects are presented in appendix D.

The temperature-corrected experimental joint deflections for loads applied at joint 10 in the X_1-, -X_2-, and X_1X_2-directions are listed in table V. The reader is cautioned that the tip loads presented in table V are not the same for all trusses or loading directions. This table shows that the deflection of each truss was essentially independent of the direction of loading. For instance, for the bonded beryllium truss, the deflection of joint 10 was 0.052, 0.051, and 0.052 inch (1.32, 1.30, and 1.32 mm) when a 100-lbf (445-N) load was applied to joint 10 in the X_1-, -X_2-, and X_1X_2-directions, respectively. The deflection data for representative joints in the three loading directions are shown in figure 9. This figure clearly illustrates the linear response of the adjusted deflections to a rapidly applied static tip load.

A comparison is shown in figure 10 between the measured joint deflections and calculated joint deflections. The deflections shown are for a tip load of 100 lbf (445 N). Agreement is reasonable (within 10 percent) at the tip for all trusses. The agreement for the aluminum trusses is less satisfactory for joints 7 and 5 than for joint 10. The calculated deflections do not include any corrections for either the joint cluster tubing or the adhesive. The calculated deflections for the bonded trusses are based on measured dimensions of the truss members. The calculated deflections for the welded truss are based on nominal dimensions of the truss members.

Although the bonded trusses were all designed for the multiple-mass loading condition, figure 10 shows that the Be-38Al and beryllium trusses are both significantly stiffer than the bonded aluminum truss. This beneficial increase in stiffness, approximately 25 percent for the Be-38Al and 50 percent for the beryllium, is in addition to the mass saving that was achieved by the substitution of these materials for aluminum. The increased stiffness is the result of the increased extensional stiffness which Be-38Al and beryllium columns exhibit when designed for the same loads as aluminum columns (see appendix B).

Truss member strains.- During a preliminary analysis of the strain-gage data from the static load tests, a large discrepancy between the experimental and calculated member strains was noted for several truss members on the bonded trusses. The anomalous strains were found to be due to partial debonding of gages. The gages presumably debonded during the dynamic tests although there was no evidence of gage failure.

Once gage debonding was suspected to be the cause of the anomalous strains, all strain gages on the trusses were checked for debonding. This checking was accomplished by applying a small uniformly distributed compressive load normal to the plane of a gage. A spring-loaded fixture was used to apply the normal force. Debonded gages exhibited an abnormally high response to the normal force. Subsequent removal of the opaque lacquer coating on several gages provided a visual confirmation of partial gage debonding on the gages which were found to be defective during the gage-checking tests. Strains measured with gages subsequently found to be debonded are not reported in this section. A listing of measured strains for the static tests are presented in table VI.

A comparison of measured and calculated member axial strains ϵ_a for loads applied in the X_1X_2-direction is shown in figure 11. For plotting convenience, the absolute values of the strains are presented in this figure. With the exception of member 7-10 on the beryllium truss, the measured and calculated axial strains are in satisfactory agreement for all trusses.

A comparison between calculated and experimental bending-strain percentages is presented in table VII for static loads applied in the X_1X_2-direction. This table also lists the experimental axial strains which were plotted in figure 11. The experimental bending strains were derived from the measured strain data by using the equations developed in appendix E. To obtain calculated bending strains, the trusses were computer-analyzed with elastically restrained members. Since the analysis was based on elastic member properties, the calculated axial strains and bending-strain percentages are shown in table VII for the 200-lbf (890-N) load as a typical example. The calculated bending-strain percentage is a constant value for all loads.

As would be expected from the linear deflection response of the trusses, the experimental bending-strain percentages were essentially constant and independent of the magnitude of the tip load. For most of the truss members, the agreement between the experimental and calculated bending-strain percentages was satisfactory.

A comparison of the calculated bending-strain percentages (table VII) for a particular truss member (7-10, for example) reveals another of the "hidden" benefits which occur when Be-38Al or beryllium is substituted for aluminum in the selected truss configuration. The bending-strain percentages are lower in the Be-38Al and beryllium truss members than those in the bonded aluminum truss. This beneficial decrease in the percentage of induced bending strain is due to the greater stiffness of the Be-38Al and beryllium trusses.

The experimental axial strains did not exhibit any time dependence during the viscoelastic studies. The experimental bending strains, however, exhibited small time-dependent changes as the truss members responded to the small changes in truss geometry.

Joint failures.- During the viscoelastic studies, all the bonded trusses were held at a maximum static load for 5 minutes. Although the trusses were designed for a multiple-mass dynamic loading condition, the static tests subjected at least one truss member to essentially its full dynamic design load. All the bonded trusses survived these maximum loads for 5 minutes when loaded in the X_1- and X_2-directions. When the maximum static load was applied in the X_1X_2-direction the bonded aluminum truss failed after 4 minutes. Member 8-10 was carrying 95 percent of the dynamic design load for this case; however, the failure occurred at the bonded split collar which joined member 2-5 to joint cluster 5 (see fig. 1). The joint failed at 55 percent of the dynamic design load for member 2-5. Examination of the split collar indicated that an adhesion failure had occurred. Since this collar had an as-extruded inside diameter, the poor adhesion was probably the result of incomplete removal of mill scale during the cleaning process.

A field repair of joint 5 was accomplished by abrasively cleaning the joint area and bonding on a spare split collar. After curing, the truss was again subjected to the maximum load in the X_1X_2-direction. After 3 minutes under load, member 2-4 failed at joint 4. The failure, cause of failure, and field repair of member 2-4 at joint 4 was the same as the failure at joint 5. The failure had occurred at 40 percent of the dynamic design load for member 2-4. After curing the second repair, the bonded aluminum truss failed again at the maximum applied load in the X_1X_2-direction. The third failure occurred at the split collar between joint 8 and member 8-10 after 3 minutes at the maximum load. The failure occurred at 95 percent of the dynamic design load for member 8-10. Examination of the failure at joint 8 did not reveal any anomalies in either the bonded surfaces or in the adhesive. No joint failures were observed on either the Be-38Al or beryllium trusses after they had been subjected to the maximum load in the X_1X_2-direction for only 1 minute.

It is important to point out that (1) the bonded trusses were only designed to sustain the maximum dynamic loads and (2) the bonded aluminum truss had been subjected to both the maximum design dynamic loads and the maximum static loads in the X_1- and X_2-directions prior to the joint failures. Nevertheless, the joint failures and the successful field repairs in the bonded aluminum truss clearly emphasize the importance of complete cleaning of aluminum parts for adhesive bonding. Also, the marked viscoelastic static deflections and the static failure in the bonded aluminum truss indicate the importance of defining the viscoelastic properties of room-temperature-curing epoxy adhesives which may be subjected to static shear loads for long periods of time.

CONCLUDING REMARKS

The applicability of thin-wall beryllium and Be-38Al tubing for lightly loaded truss-type structures has been demonstrated. The beryllium and Be-38Al trusses successfully

survived dynamic tests that were considered comparable to those used to flight-qualify unmanned spacecraft. The substantial mass savings that can be achieved by substituting beryllium or Be-38Al for aluminum tubing were verified.

In addition to being approximately 50 percent lighter, the beryllium and Be-38Al trusses were stiffer than the comparable aluminum truss. This increased stiffness produced beneficial increases in the first-bending-mode frequencies and also reduced the relative magnitude of induced bending loads in the truss members. The dynamic-test and static-test results demonstrated that the responses of the beryllium and Be-38Al trusses were as predictable as those for the two aluminum trusses.

The successful development of a low-mass joint design which eliminates many of the problems associated with the fabrication of beryllium tubing has been demonstrated. The adhesively bonded joint design selected resulted in truss joint mass fractions which were 17 and 35 percent for the bonded aluminum and beryllium trusses, respectively. Joint failures observed during static tests on the bonded aluminum truss were attributed to the viscoelastic properties of the adhesive.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., March 20, 1969,
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APPENDIX A

CONVERSION OF U.S. CUSTOMARY UNITS TO SI UNITS

The International System of Units (SI) was adopted by the Eleventh General Conference on Weights and Measures in 1960 (ref. 6). Conversion factors used herein are given in the following table:

Physical quantity	U.S. Customary Unit	Conversion factor (*)	SI Unit (**)
Length	in.	0.0254	meters (m)
Load	lbf	4.448	newtons (N)
Mass	lbm	0.4536	kilograms (kg)
Temperature	$^{\circ}$F	$\frac{5}{9}$(F + 460)	degrees Kelvin ($^{\circ}$K)
Density	lbm/in^3	27.68×10^3	kilograms/meter^3 (kg/m^3)
Modulus; stress	psi = lbf/in^2	6895	newtons/meter^2 (N/m^2)
	ksi = kips/in^2	6.895×10^6	

*Multiply value given in U.S. Customary Units by conversion factor to obtain equivalent value in SI Unit.

**Prefixes to indicate multiple of units are as follows:

Prefix	Multiple
micro (μ)	10^{-6}
milli (m)	10^{-3}
kilo (k)	10^3
mega (M)	10^6
giga (G)	10^9

APPENDIX B

TRUSS CONFIGURATION SELECTION AND MATERIALS COMPARISONS

This appendix presents the results of the truss configuration studies which were performed to select an efficient and representative truss configuration. This appendix also presents some materials-comparison relationships for truss-type structures.

Configuration Selection

A variety of truss configurations conforming to the truss design criteria were analyzed with the aid of a digital-computer program (ref. 7). The basic computer program (whose output included frequencies, mode shapes, and member forces during free vibration for the first six modes) was modified to include the calculation of member stresses, member masses between joint centers, and total truss mass. The calculation of total truss mass included an estimate of joint mass. The expression used to calculate joint mass was based on a mass analysis of typical spacecraft joints. In these joints, the truss members are usually mechanically fastened to a joint cluster machined from solid stock. Aluminum was selected as the joint material for all trusses. During the analysis, truss members were assumed to be pinned-end columns and an amplification factor (transmissibility) of 20 was assumed for the 2g-peak lateral acceleration. Truss members in a given tier were sized for the largest member force that occurred in that tier.

Several of the more efficient truss configurations analyzed are shown in figure 12. These trusses were analyzed and sized for both the experimental package masses shown in figure 2 and for a single 5.0-lbm (2.3-kg) simulated experimental package at the top of the truss. These two loading configurations are referred to as the multiple-mass and single-mass loading conditions, respectively.

The configuration and preliminary member sizing studies indicated that the dynamic loads governed the design. The loads due to the longitudinal acceleration were about 15 percent of the lateral dynamic loads. The dynamic loads were such that most of the truss members were lightly loaded and were sized by column elastic stability considerations; consequently, stresses were low.

A summary of the truss masses for both loading conditions and with beryllium substituted for aluminum tubing in the truss members is presented in table VIII. The following observations can be made from this table and figure 12:

(1) The minimum mass truss is three-legged.

(2) Beryllium tubing substituted for aluminum tubing resulted in an overall mass saving of 20 to 27 percent.

(3) The ratio of beryllium tubing mass to aluminum tubing mass was approximately 45 percent and was not strongly influenced by either the loading condition or the truss configuration.

(4) For the beryllium trusses, joint mass constituted from 60 to 80 percent of the total truss mass based on the assumed mechanical joints. Subsequent development of an adhesively bonded joint for the experimental trusses that were fabricated resulted in joints which were only 35 percent of the total truss mass. Consequently, both the aluminum and beryllium bonded trusses were lighter than was predicted by the configuration studies. The results of the configuration and preliminary sizing studies confirmed the potential of beryllium tubing for lightly loaded, truss-type structures. The configuration selected (table VIII, truss 1) was the most efficient configuration for the multiple-mass loading condition in both the aluminum and beryllium trusses. This configuration was not the most efficient for the single-mass loading condition.

Materials-Comparison Relationships for Truss-Type Structures

During the configuration selection studies, the beryllium trusses were lighter than a comparable aluminum truss. The beryllium trusses also used smaller diameter truss members and were stiffer than the comparable aluminum trusses.

The following discussion presents elementary materials-comparison expressions which illustrate "hidden" benefits (such as smaller diameter truss members) which result from the substitution of Be-38Al or beryllium thin-wall tubing for aluminum tubing in lightly loaded, truss-type structures.

The truss members for the trusses in this investigation were all designed as pinned-end columns. The column design loads were those associated with the maximum dynamic response in the multiple-mass loading condition. For a given truss tier, these dynamic design loads were essentially independent of truss member material. The column design parameters P and L were of such value that all columns had a low structural index (P/L^2). Since minimum gage considerations usually preclude local buckling failures in lightly loaded columns, this discussion will assume the same minimum wall thickness for all materials.

The buckling load of a thin-wall, tubular, pinned-end column is

$$P_{cr} = \frac{\pi^3 E D^3 t}{8L^2} \tag{B1}$$

With the use of equation (B1), the relationship between the diameters of an aluminum and beryllium column can be expressed by

$$\frac{D_{Be}}{D_{Al}} = \left(\frac{E_{Al}}{E_{Be}}\right)^{1/3} \tag{B2}$$

or with the use of the material properties listed in table IX,

$$D_{Be} = 0.63D_{Al} \tag{B3}$$

The stiffness of a pinned-end truss network is a function of the extensional stiffnesses of its members – that is,

$$\delta \approx \frac{1}{E} \sum_{i=1}^{n} \frac{P_i L_i}{A_i} \tag{B4}$$

Since the member loads and member lengths are the same for a given truss configuration, it can be assumed that the extensional stiffness of a single truss member is representative of truss stiffness for the purposes of a materials comparison. Utilization of equation (B4) for a single truss member leads to the following extensional-stiffness relationship between an aluminum and a beryllium truss:

$$\frac{\delta_{Be}}{\delta_{Al}} \approx \frac{D_{Al}E_{Al}}{D_{Be}E_{Be}} \tag{B5}$$

Substituting from equation (B2) for D_{Al}/D_{Be} yields

$$\frac{\delta_{Be}}{\delta_{Al}} \approx \left(\frac{E_{Al}}{E_{Be}}\right)^{2/3} \tag{B6}$$

or

$$\delta_{Be} \approx 0.40\delta_{Al} \tag{B7}$$

As a first approximation, the vibrational frequency of a massless cantilever with a single tip mass is

$$f \approx C\left(\frac{1}{\delta}\right)^{1/2}$$

From this expression

$$\frac{f_{Be}}{f_{Al}} \approx \left(\frac{\delta_{Al}}{\delta_{Be}}\right)^{1/2} \approx \left(\frac{E_{Be}}{E_{Al}}\right)^{1/3} \tag{B8}$$

or

$$f_{Be} \approx 1.53 f_{Al} \tag{B9}$$

For equal mass joints, the mass saving which results from the substitution of beryllium for aluminum in lightly loaded trusses can be developed from equation (B2) and is

$$\frac{m_{Be}}{m_{Al}} \approx \frac{\left(\frac{\rho}{E^{1/3}}\right)_{Be}}{\left(\frac{\rho}{E^{1/3}}\right)_{Al}} \tag{B10}$$

or

$$m_{Be} \approx 0.42 m_{Al} \tag{B11}$$

Expressions similar to equations (B3), (B7), (B9), and (B11) can be developed for the substitution of Be-38Al tubing for aluminum tubing. These expressions are

$$\left.\begin{aligned} D_{Be\text{-}38Al} &= 0.71 D_{Al} \\ \delta_{Be\text{-}38Al} &\approx 0.50 \delta_{Al} \\ f_{Be\text{-}38Al} &\approx 1.41 f_{Al} \\ m_{Be\text{-}38Al} &\approx 0.54 m_{Al} \end{aligned}\right\} \tag{B12}$$

In summary, the substitution of beryllium or Be-38Al thin-wall tubing for aluminum tubing in a lightly loaded, truss-type structure can result in significant mass savings. In addition to being lighter, the beryllium and Be-38Al trusses will have smaller diameter tubing, will be stiffer, and will exhibit higher frequency vibrational resonances than a comparable aluminum truss.

APPENDIX C

TRUSS FABRICATION AND ASSEMBLY

This appendix describes the fabrication and assembly of the three bonded trusses. The fabrication and assembly of the welded aluminum truss is not described since this truss was fabricated with the use of standard inert gas welding and welding-fixture procedures.

Materials

The pertinent material properties of the aluminum, Be-38Al, and beryllium extruded tubing used in the final design of the bonded trusses are shown in table IX. A detailed description of the mechanical properties and column behavior of the beryllium tubing and the as-extruded Be-38Al tubing used for the trusses is presented in references 4 and 5, respectively. The beryllium tubing is referred to in reference 4 as the type BL tubing. The nominal mechanical properties of the 6061-T6 aluminum tubing used for the joint clusters, split collars, and for the truss members in the aluminum trusses are taken from reference 8. The nominal wall thickness of the Be-38Al and beryllium truss members was 0.020 inch (0.51 mm). The wall thickness of the aluminum tubing ranged from 0.020 to 0.058 inch (0.51 to 1.47 mm).

The minimum diameter restriction (0.25 inch (6.4 mm)) controlled the size of members 7-8, 7-9, and 8-9 (fig. 1) on the Be-38Al and beryllium trusses. Column stability (pinned-end) considerations controlled the design of the other truss members. The range of truss member and joint cluster diameters is presented in table X. The welded aluminum truss was sized for the single-mass loading condition; consequently, its members were smaller than those of the bonded aluminum truss which was sized for the multiple-mass loading condition.

The joints of the bonded trusses were designed to be twice as strong as the truss members. The adhesive selected was EPON 911S. The design shear strength of the adhesive was based on the bonding studies and was 2000 psi (13.8 MN/m^2).

Joints

The aluminum tubing used to fabricate the joint clusters for joints 7, 8, and 9 (fig. 1) of the bonded trusses was machined and welded utilizing the fixture shown in figure 13. The fabrication fixture completely supported the joint cluster during welding and could be rapidly inverted in the welding chamber to weld opposite sides of the cluster (fig. 13(b)). A similar fixture was used to fabricate joints 4, 5, and 6. To fabricate a joint, the truss members that formed either a vertical or horizontal plane were machined and welded

first. The joint fabrication fixture was then utilized to machine the intersections of these planes (fig. 14(a)). Final fabrication of the joint clusters included additional electron-beam welding passes to form the cluster (fig. 14(b)).

Both the welding schedule and the design of the welding fixture were chosen to minimize welding distortions. The welding schedule included balanced initial tack and final welding passes. Inert gas welding was used to patch the occasional small burnthroughs which occurred at the beginning and end of some of the more complex joint intersections. Inert gas welding was also used to "pull" joints that had been slightly distorted during the final electron-beam welding passes. The average net-section tensile strength of the as-welded tubing was found to be 25 ksi (172 MN/m^2). Tests on incompletely welded tubing (approximately 50 percent of the tubing circumference) were also performed. These tests established that the terminations of the incomplete welds did not appreciably affect the net-section tensile strength of the as-welded joint. Based on the results of these tests, no attempt was made to weld completely the apex (crotch) of the tubing intersections which formed vertical planes. After welding, the joint cluster tubing was cut to final length. The finished joint clusters for the bonded aluminum truss are shown in figure 15. Also shown in this figure are the footpads which formed joints 1, 2, and 3 and the 5-lbm (2.3-kg) simulated experimental package which formed the joint assembly for joint 10.

The split collars used to join the truss members to the joint clusters were machined from aluminum tubing. These collars had a minimum wall thickness of 0.020 inch (0.51 mm) and a constant outside diameter. Some of the collars were stepped, on the inside diameter, to accommodate differences in truss member and joint tubing diameters. These diameter differences occurred because the vertical members of the joint clusters were constrained to the same diameters.

To fabricate the truss members, they were cut to length. No machining of the diameter of truss members was done. Truss members were cut to provide clearance (0.005 inch (0.13 mm)) between the truss members and the joint clusters to facilitate truss assembly. The truss members, joint clusters, and split collars were cleaned for adhesive bonding by utilizing the procedures described in reference 4. Identical cleaning procedures were used for both the beryllium and Be-38Al tubing.

Truss Assembly

The same basic fixture was used to assemble all the bonded trusses. This truss assembly fixture (fig. 16(a)) was used to locate the footpads, joint clusters, and the interior cone of joint 10. The vertical truss members were bonded in place first (figs. 16(b) and 16(c)). These joints were cured overnight and then the horizontal truss members were bonded (fig. 16(d)).

The rods used to locate the joint clusters are shown in figure 17(a). These machined rods incorporated an expanding tip which gripped the inside diameter of the cluster tubing. To accommodate the diameter differences of the horizontal members in the different trusses, the vee-grooves in the horizontal location plates were sized for the aluminum truss members. Spacers were used for the other trusses. To bond the vertical members (fig. 17(b)), the adhesive was evenly spread on the inside of the collars. The split collars were located on the joint center line by using plastic tape wound circumferentially around either the cluster or member tubing. The collars were clamped in place with plastic strips and the excess adhesive was wiped off.

A minimum adhesive thickness of 0.005 inch (0.13 mm) was maintained at the bond line by adding 1 percent by mass sieved (-120+140 mesh) glass beads to the adhesive before mixing. It is interesting to note that the tape used to locate the collars is normally used for identification tags and that the joint clamps are normally used to secure electrical wiring.

After the vertical truss members had cured overnight, the cluster locating rods were removed and the horizontal members were clamped in place and bonded (fig. 17(c)). The bonded joints were allowed to cure for 5 days before the truss was lifted free of the assembly fixture. The as-fabricated bonded beryllium truss is shown in figure 4.

APPENDIX D

VISCOELASTIC TRUSS BEHAVIOR

This appendix presents the results of a cursory study which was performed to establish the time and temperature dependence of joint deflection to permit a comparison between calculated and experimental joint deflections. In preliminary static tests, the response of the bonded aluminum truss to incrementally applied loads was nonlinear. When the test load was applied rapidly and the bonded trusses were allowed to recover between each load application, joint deflections were a linear function of the applied tip load (fig. 18).

The time dependence of tip (joint 10) deflection for the bonded Be-38Al truss loaded in the X_1-direction is shown in figure 19. Similar viscoelastic deflection behavior was exhibited by the other bonded trusses. For a given tip load, the direction of tip load application did not significantly alter the response shown in figure 19. When given sufficient time to recover, joints in the bonded trusses did not exhibit any permanent set.

The temperature dependence of the bonded-truss tip deflections is shown in figure 20. A thermometer suspended near joint 7 was used to measure the test environment temperature. In this figure, tip deflection immediately after the application of the test load has been normalized with respect to the calculated tip deflection. The data shown include the results of tests with several combinations of tip loads and loading directions for each bonded truss. These data show that the normalized tip deflections of the bonded trusses were a linear function of the test temperature with the same slope for all the bonded trusses. The similar temperature dependence of the bonded trusses was expected since the same adhesive was used for all bonded joints. The welded-aluminum-truss tip deflections were independent of the test temperature.

To provide a basis for comparison between calculated and experimental joint deflections, the joint-deflection data reported in table V were corrected to a test temperature of 80° F (300° K). This correction was applied as follows:

$$\delta_{corrected} = \delta_{apparent}\left[1 - K\left(T - T_o\right)\right]$$

where

δ joint deflection, inch (mm)

$K = 0.01/^\circ F$ $(0.0055/^\circ K)$ (calculated from slope of curves in fig. 20)

T	test temperature, ^{o}F (^{o}K)
T_o	reference temperature, 80^{o} F (300^{o} K)

APPENDIX E

CALCULATION OF AXIAL AND BENDING STRAINS

Although the primary loads in the truss members were axially applied, the joints were capable of transmitting induced bending loads. To evaluate these induced bending loads, three strain gages were bonded to the center of several representative truss members. The gages were bonded at 90° intervals about the circumference of the member. The fact that the measured strains included an axial-strain component and a bending-strain component which varied sinusoidally around the circumference of the member leads to the following equations:

$$\left.\begin{aligned} \epsilon_1 &= \epsilon_a + \epsilon_b \sin \varphi \\ \epsilon_2 &= \epsilon_a + \epsilon_b \sin(\varphi + 90^\circ) \\ \epsilon_3 &= \epsilon_a + \epsilon_b \sin(\varphi + 180^\circ) \end{aligned}\right\} \tag{E1}$$

With the use of trigonometric identities, equations (E1) can be solved to yield

$$\left.\begin{aligned} \epsilon_a &= \frac{\epsilon_1 + \epsilon_3}{2} \\ \epsilon_b &= \left[\left(\epsilon_1 - \epsilon_a\right)^2 + \left(\epsilon_2 - \epsilon_a\right)^2\right]^{1/2} \\ \varphi &= \sin^{-1} \frac{\epsilon_1 - \epsilon_a}{\epsilon_b} \end{aligned}\right\} \tag{E2}$$

Since equations (E2) yield only positive values of ϵ_b, the maximum member strain is calculated by making the sign of ϵ_b the same as ϵ_a:

$$\pm\epsilon_{max} = \pm\epsilon_a \pm \left|\epsilon_b\right| \tag{E3}$$

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TABLE I.- MASS SUMMARY OF BONDED TRUSSES

Component	Truss					
	Aluminum		Be-38Al		Beryllium	
	lbm	kg	lbm	kg	lbm	kg
Truss members	2.504	1.137	0.970	0.441	0.906	0.412
Joint clusters	.323	.147	.284	.129	.280	.127
Split collars	.129	.058	.214	.097	.179	.081
Adhesive	.044	.020	.045	.020	.051	.023
Total mass	3.000	1.362	1.513	0.687	1.416	0.643

TABLE II.- TYPICAL SCHEDULE FOR TRUSS-VIBRATION TEST

Run	Excitation reference (see fig. 1)	Loading condition	Input level, g units (a)	Test type (b)
1	X_1	Single mass	1.0	Sweep
2			.5	Dwell
3			1.0	Dwell
4	X_2	Single mass	1.0	Sweep
5			.5	Dwell
6			1.0	Dwell
7			2.0	Sweep
8	X_2	Multiple mass	1.0	Sweep
9			.5	Dwell
10			1.0	Dwell
11			2.0	Sweep
12	X_1	Multiple mass	1.0	Sweep
13			.5	Dwell
14			1.0	Dwell
15			2.0	Sweep
16	X_1X_2	Multiple mass	1.0	Sweep
17			.5	Dwell
18			1.0	Dwell
19			2.0	Sweep
20	X_1X_2	Single mass	1.0	Sweep
21			.5	Dwell
22			1.0	Dwell

[a]All excitation was sinusoidal. Control level was based on peak acceleration.

[b]Sweep tests were run at two octaves per minute from 500 to 10 hertz. Dwell tests established maximum tip response at lowest response frequency.

TABLE III.- COMPARISON OF CALCULATED AND EXPERIMENTAL FIRST-BENDING RESONANT FREQUENCY FOR TRUSSES EXCITED IN X_1X_2-DIRECTION

Truss	Loading condition	Calculated first-bending-mode frequency, f_{calc}, Hz	$\frac{f_{exp}}{f_{calc}}$			
			Dwell test		Sweep test	
Input level			0.5g	1.0g	1.0g	2.0g
Welded aluminum	Single mass	39.7	0.94	0.94	0.94	----
	Multiple mass	33.7	.90	.94	.89	0.78
Bonded aluminum	Single mass	42.3	0.97	0.98	0.97	----
	Multiple mass	37.0	.93	.94	.94	0.96
Bonded Be-38Al	Single mass	50.0	1.00	1.00	1.00	----
	Multiple mass	43.7	.94	.96	.96	0.98
Bonded beryllium	Single mass	57.4	1.02	1.01	1.01	----
	Multiple mass	49.9	.97	.98	.98	1.02

TABLE IV.- ABSOLUTE VALUES OF EXPERIMENTAL MEMBER STRAINS AT MAXIMUM DYNAMIC RESPONSE

[Multiple-mass loading condition; 2g-peak input in X_1X_2-direction]

Truss response frequency	Member	Measured strain			ϵ_{av}	ϵ_{max}	$\frac{\epsilon_b}{\epsilon_a}(100)$
		ϵ_1	ϵ_2	ϵ_3			
Bonded aluminum (35 Hz)	1-6	371×10^{-6}	367×10^{-6}	347×10^{-6}	359×10^{-6}	373×10^{-6}	4
	2-4	370	302	310	340	389	14
	4-5	(a)	357	376	---------	---------	--
	6-9	325	312	287	306	326	6
	7-9	372	(a)	363	367	---------	--
	7-10	290	312	242	266	318	20
	8-10	476	543	429	453	556	21
Bonded Be-38Al (43 Hz)	1-6	161×10^{-6}	164×10^{-6}	(a)	---------	---------	--
	2-4	157	145	135×10^{-6}	146×10^{-6}	157×10^{-6}	7
	4-5	212	226	222	217	228	5
	6-9	171	(a)	(a)	---------	---------	--
	7-9	242	222	215	228	243	7
	7-10	126	95	95	110	132	20
	8-10	257	225	228	243	265	9
Bonded beryllium (51 Hz)	1-6	(a)	(a)	89×10^{-6}	---------	---------	--
	2-4	88×10^{-6}	79×10^{-6}	78	83×10^{-6}	90×10^{-6}	8
	4-5	81	83	(a)	---------	---------	--
	6-9	90	(a)	74	82	---------	--
	7-9	79	79	61	70	83	18
	7-10	87	(a)	64	76	---------	--
	8-10	(a)	111	(a)	---------	---------	--

[a]Strain gages later found to be partially debonded.

TABLE V.- EXPERIMENTAL JOINT DEFLECTIONS[a] FOR CONCENTRATED LOAD APPLIED TO TRUSS AT JOINT 10

(a) Load in X_1-direction

Truss	Joint	δ, in.	δ, mm	δ, in.	δ, mm	δ, in.	δ, mm
		P = 100 lbf	(445 N)	P = 200 lbf	(890 N)	P = 250 lbf	(1110 N)
Welded aluminum	10	0.118	3.00	0.236	5.99	0.295	7.49
	8	.056	1.42	.112	2.84	.141	3.58
	7	.052	1.32	.104	2.64	.130	3.30
	5	.010	.25	.020	.51	.025	.64
	4	.014	.36	.028	.71	.036	.91
		P = 100 lbf	(445 N)	P = 200 lbf	(890 N)	P = 250 lbf	(1110 N)
Bonded aluminum	10	0.104	2.64	0.207	5.26	0.265	6.73
	8	.042	1.07	.086	2.18	.109	2.77
	7	.039	.99	.080	2.03	.102	2.59
	5	.007	.18	.008	.20	.015	.38
	4	.009	.23	.020	.51	.026	.66
		P = 100 lbf	(445 N)	P = 200 lbf	(890 N)	P = 250 lbf	(1110 N)
Bonded Be-38Al	10	0.068	1.73	0.139	3.53	0.172	4.37
	8	-----	----	.051	1.30	.064	1.63
	7	.024	.61	.050	1.27	.063	1.60
	5	.004	.10	.009	.23	.011	.28
	4	.006	.15	.011	.28	.015	.38
		P = 100 lbf	(445 N)	P = 200 lbf	(890 N)	P = 250 lbf	(1110 N)
Bonded beryllium	10	0.052	1.32	0.107	2.72	0.134	3.40
	8	.020	.51	.043	1.09	.054	1.37
	7	.019	.48	.042	1.07	.053	1.35
	5	.004	.10	.007	.18	.009	.23
	4	.005	.13	.010	.25	.013	.33

[a]Deflections given for bonded trusses are corrected to 80° F (300° K) (see appendix D).

TABLE V.- EXPERIMENTAL JOINT DEFLECTIONS[a] FOR CONCENTRATED LOAD APPLIED TO TRUSS AT JOINT 10 – Continued

(b) Load in $-X_2$-direction

Truss	Joint	δ		δ		δ	
		in.	mm	in.	mm	in.	mm
		P = 100 lbf	(445 N)	P = 200 lbf	(890 N)	P = 250 lbf	(1110 N)
Welded aluminum	10	0.115	2.92	0.235	5.97	0.295	7.49
	9	.057	1.45	.113	2.87	.144	3.66
	8	.055	1.40	.109	2.77	-----	----
	7	.059	1.50	.115	2.92	.148	3.76
	6	.013	.33	.025	.64	.031	.79
	4	.011	.28	.022	.56	.029	.74
		P = 100 lbf	(445 N)	P = 200 lbf	(890 N)	P = 300 lbf	(1335 N)
Bonded aluminum	10	0.107	2.72	0.210	5.33	0.322	8.18
	9	.042	1.07	.085	2.16	.129	3.28
	8	.041	1.04	.084	2.13	.126	3.20
	7	.044	1.12	.086	2.18	.136	3.45
	6	.009	.23	.018	.46	.028	.71
	4	.008	.20	.016	.41	.025	.64
		P = 100 lbf	(445 N)	P = 150 lbf	(668 N)	P = 200 lbf	(890 N)
Bonded Be-38Al	10	0.072	1.83	0.111	2.82	0.145	3.68
	9	.026	.66	.041	1.04	.054	1.37
	8	.026	.66	.040	1.02	.052	1.32
	7	.027	.69	.040	1.02	.054	1.37
	6	.005	.13	.008	.20	.011	.28
	4	.004	.10	.007	.18	.010	.25
		P = 100 lbf	(445 N)	P = 150 lbf	(668 N)	P = 200 lbf	(890 N)
Bonded beryllium	10	0.051	1.30	0.075	1.91	0.101	2.57
	9	.020	.51	.029	.74	.040	1.02
	8	.020	.51	.029	.74	.040	1.02
	7	.019	.48	.029	.74	.039	.99
	6	.004	.10	.006	.15	.009	.23
	4	.004	.10	.005	.13	.007	.18

[a]Deflections given for bonded trusses are corrected to 80° F (300° K) (see appendix D).

TABLE V.- EXPERIMENTAL JOINT DEFLECTIONS[a] FOR CONCENTRATED LOAD APPLIED TO TRUSS AT JOINT 10 – Concluded

(c) Load in X_1X_2-direction

Truss	Joint	δ, in.	δ, mm	δ, in.	δ, mm	δ, in.	δ, mm
		P = 100 lbf	(445 N)	P = 200 lbf	(890 N)	P = 250 lbf	(1110 N)
Welded aluminum	10	0.119	3.02	0.237	6.02	0.310	7.87
	9	.053	1.35	.107	2.72	.141	3.58
	8	.053	1.35	.107	2.72	.143	3.63
	5	.012	.30	.025	.64	.036	.92
	4	.009	.23	.018	.46	.027	.69
		P = 100 lbf	(445 N)	P = 200 lbf	(890 N)	P = 225 lbf	(1000 N)
Bonded aluminum	10	0.105	2.67	0.210	5.33	0.240	6.10
	9	.040	1.02	.082	2.08	.097	2.46
	8	.043	1.09	.090	2.29	.104	2.64
	5	.008	.20	.018	.46	.021	.53
	4	.007	.18	.015	.38	.017	.43
		P = 100 lbf	(445 N)	P = 200 lbf	(890 N)	P = 225 lbf	(1000 N)
Bonded Be-38Al	10	0.068	1.73	0.137	3.48	0.163	4.14
	9	.026	.66	.053	1.35	.061	1.55
	8	.026	.66	.053	1.35	.061	1.55
	5	.006	.15	.011	.28	.016	.41
	4	.004	.10	.010	.25	.010	.25
		P = 100 lbf	(445 N)	P = 200 lbf	(890 N)	P = 225 lbf	(1000 N)
Bonded beryllium	10	0.052	1.32	0.105	2.67	0.119	3.02
	9	.022	.56	.043	1.09	.048	1.22
	8	.023	.58	.044	1.12	.049	1.24
	5	.006	.15	.011	.28	.012	.30
	4	.004	.10	.009	.23	.011	.28

[a]Deflections given for bonded trusses are corrected to 80° F (300° K) (see appendix D).

TABLE VI.- EXPERIMENTAL MEMBER STRAINS FOR CONCENTRATED LOAD APPLIED TO TRUSS AT JOINT 10

(a) Load in X_1-direction

Truss	Member	ϵ_1	ϵ_2	ϵ_3	ϵ_1	ϵ_2	ϵ_3	ϵ_1	ϵ_2	ϵ_3
		P = 100 lbf (445 N)			P = 200 lbf (890 N)			P = 250 lbf (1110 N)		
Welded aluminum	4-6	-394×10^{-6}	-433×10^{-6}	-364×10^{-6}	-785×10^{-6}	-881×10^{-6}	-721×10^{-6}	-962×10^{-6}	-1114×10^{-6}	-921×10^{-6}
	4-7	----------	----------	----------	----------	----------	----------	----------	----------	----------
	6-9	23	-14	-19	45	-30	-39	64	-33	50
	8-9	485	412	419	969	833	849	1277	1009	995
	7-10	413	487	437	830	965	868	1031	1187	1085
		P = 100 lbf (445 N)			P = 200 lbf (890 N)			P = 300 lbf (1335 N)		
Bonded aluminum	1-6	217×10^{-6}	182×10^{-6}	187×10^{-6}	432×10^{-6}	380×10^{-6}	386×10^{-6}	645×10^{-6}	573×10^{-6}	581×10^{-6}
	2-4	7	16	-9	23	33	-19	29	48	-25
	4-5	----------	114	105	----------	231	218	----------	335	325
	6-9	14	-12	-18	30	-15	-24	43	-21	-37
	7-9	-134	----------	-111	-267	----------	-213	-412	----------	-322
	7-10	531	470	425	1054	943	876	1566	1418	1328
	8-10	-260	-174	-221	-507	-331	-427	-761	-487	-642
		P = 100 lbf (445 N)			P = 150 lbf (668 N)			P = 200 lbf (890 N)		
Bonded Be-38Al	1-6	112×10^{-6}	116×10^{-6}	----------	174×10^{-6}	180×10^{-6}	----------	228×10^{-6}	235×10^{-6}	----------
	2-4	2	7	----------	4	12	----------	2	12	----------
	4-5	86	89	89×10^{-6}	132	138	137×10^{-6}	171	178	178×10^{-6}
	6-9	7	----------	----------	13	----------	----------	15	----------	----------
	7-9	-87	-87	-90	-130	-131	-136	-180	-180	-188
	7-10	368	352	379	572	547	583	756	728	768
	8-10	-182	-123	-142	-279	-183	-214	-372	-250	-292
		P = 100 lbf (445 N)			P = 150 lbf (668 N)			P = 200 lbf (890 N)		
Bonded beryllium	1-6	----------	----------	85×10^{-6}	----------	----------	130×10^{-6}	----------	----------	173×10^{-6}
	2-4	1×10^{-6}	3×10^{-6}	1	1×10^{-6}	5×10^{-6}	1	1×10^{-6}	6×10^{-6}	-1
	4-5	50	46	----------	76	73	----------	96	101	----------
	6-9	3	----------	-3	5	----------	-2	4	----------	-5
	7-9	-46	-45	-38	-68	-67	-58	-91	-92	-79
	7-10	229	----------	174	343	----------	276	456	----------	371
	8-10	----------	-131	----------	----------	-196	----------	----------	-173	----------

TABLE VI.- EXPERIMENTAL MEMBER STRAINS FOR CONCENTRATED LOAD APPLIED TO TRUSS AT JOINT 10 – Continued

(b) Load in $-X_2$-direction

Truss	Member	ϵ_1	ϵ_2	ϵ_3	ϵ_1	ϵ_2	ϵ_3	ϵ_1	ϵ_2	ϵ_3
		P = 100 lbf (445 N)			P = 200 lbf (890 N)			P = 250 lbf (1110 N)		
Welded aluminum	4-6	10×10^{-6}	2×10^{-6}	6×10^{-6}	16×10^{-6}	-1×10^{-6}	-1×10^{-6}	18×10^{-6}	-3×10^{-6}	-2×10^{-6}
	4-7	173	139	93	338	271	187	425	235	341
	6-9	-293	-235	-200	-582	-567	-434	-735	-698	-531
	8-9	6	1	3	-6	-25	-24	-12	-40	-39
	7-10	74	7	-52	136	4	-113	169	7	-137
		P = 100 lbf (445 N)			P = 200 lbf (890 N)			P = 250 lbf (1110 N)		
Bonded aluminum	1-6	-138×10^{-6}	-123×10^{-6}	-96×10^{-6}	-276×10^{-6}	-249×10^{-6}	-193×10^{-6}	-341×10^{-6}	-312×10^{-6}	-236×10^{-6}
	2-4	267	217	204	527	450	421	654	564	529
	4-5	----------	-187	-201	----------	-372	-406	----------	-461	-502
	6-9	-233	-217	-186	-478	-436	-361	-600	-539	-444
	7-9	230	----------	179	459	----------	363	564	----------	461
	7-10	-1	-69	-4	1	-136	-9	-3	-169	-4
	8-10	445	440	371	881	872	752	1109	1093	950
		P = 100 lbf (445 N)			P = 200 lbf (890 N)			P = 250 lbf (1110 N)		
Bonded Be-38Al	1-6	-74×10^{-6}	-69×10^{-6}	----------	-144×10^{-6}	-140×10^{-6}	----------	-183×10^{-6}	-170×10^{-6}	----------
	2-4	123	126	----------	248	254	----------	313	322	----------
	4-5	-151	-155	-151×10^{-6}	-306	-312	-295×10^{-6}	-393	-396	-373×10^{-6}
	6-9	-170	----------	----------	-355	----------	----------	-458	----------	----------
	7-9	160	-59	160	322	317	313	398	395	398
	7-10	-36	4	36	-71	5	69	-94	3	87
	8-10	327	294	258	648	593	526	814	747	665
		P = 100 lbf (445 N)			P = 200 lbf (890 N)			P = 250 lbf (1110 N)		
Bonded beryllium	1-6	----------	----------	-49×10^{-6}	----------	----------	-72×10^{-6}	----------	----------	-119×10^{-6}
	2-4	121×10^{-6}	110×10^{-6}	109	237×10^{-6}	223×10^{-6}	220	295×10^{-6}	281×10^{-6}	277
	4-5	-90	-80	----------	-165	-183	----------	-226	-211	----------
	6-9	-114	----------	-99	-227	----------	-193	-285	----------	-241
	7-9	76	73	66	158	154	141	192	187	173
	7-10	-8	----------	4	-9	----------	11	-14	----------	10
	8-10	----------	194	----------	----------	320	----------	----------	485	----------

TABLE VI.- EXPERIMENTAL MEMBER STRAINS FOR CONCENTRATED LOAD APPLIED TO TRUSS AT JOINT 10 – Concluded

(c) Load in X_1X_2-direction

Truss	Member	ϵ_1	ϵ_2	ϵ_3	ϵ_1	ϵ_2	ϵ_3	ϵ_1	ϵ_2	ϵ_3
		P = 100 lbf (445 N)			P = 200 lbf (890 N)			P = 250 lbf (1110 N)		
Welded aluminum	4-6	273×10^{-6}	296×10^{-6}	267×10^{-6}	541×10^{-6}	585×10^{-6}	531×10^{-6}	678×10^{-6}	731×10^{-6}	667×10^{-6}
	4-7	-44	-73	-81	-89	-151	-167	-109	-189	-210
	6-9	-219	-189	-146	-448	-381	-284	-568	-477	-348
	8-9	-338	-299	-307	-682	-600	-617	-853	-748	-769
	7-10	-249	-359	-349	-497	-717	-695	-619	-896	-867
		P = 100 lbf (445 N)			P = 200 lbf (890 N)			P = 225 lbf (1000 N)		
Bonded aluminum	1-6	-262×10^{-6}	-219×10^{-6}	-202×10^{-6}	-518×10^{-6}	-419×10^{-6}	-391×10^{-6}	-585×10^{-6}	-477×10^{-6}	-432×10^{-6}
	2-4	176	139	148	359	291	303	407	311	337
	4-5	----------	-217	-219	----------	-439	-432	----------	-487	-487
	6-9	-192	-149	-122	-379	-291	-230	-434	-317	-243
	7-9	251	----------	203	511	----------	411	537	----------	451
	7-10	-382	-402	-301	-777	-789	-571	-877	-907	-645
	8-10	499	432	424	979	876	865	1093	985	968
		P = 100 lbf (445 N)			P = 200 lbf (890 N)			P = 225 lbf (1000 N)		
Bonded Be-38Al	1-6	-133×10^{-6}	-124×10^{-6}	----------	-278×10^{-6}	-248×10^{-6}	----------	-284×10^{-6}	-281×10^{-6}	----------
	2-4	81	85	----------	172	173	----------	190	195	----------
	4-5	-165	-172	-139×10^{-6}	-334	-338	-336×10^{-6}	-370	-388	-378×10^{-6}
	6-9	-130	----------	----------	-262	----------	----------	-302	----------	----------
	7-9	169	174	185	348	354	368	383	392	427
	7-10	-280	-249	-252	-569	-490	-503	-637	-548	-562
	8-10	352	301	288	707	620	596	791	696	673
		P = 100 lbf (445 N)			P = 200 lbf (890 N)			P = 225 lbf (1000 N)		
Bonded beryllium	1-6	----------	----------	-96×10^{-6}	----------	----------	-192×10^{-6}	----------	----------	-210×10^{-6}
	2-4	82×10^{-6}	74×10^{-6}	76	163×10^{-6}	151×10^{-6}	154	186×10^{-6}	171×10^{-6}	176
	4-5	-100	-89	----------	-200	-180	----------	-224	-195	----------
	6-9	-85	----------	-66	-171	----------	-130	-193	----------	-140
	7-9	85	83	75	172	167	152	199	191	174
	7-10	-167	----------	-124	-357	----------	-256	-390	----------	-265
	8-10	----------	222	----------	----------	448	----------	----------	502	----------

TABLE VII.- EXPERIMENTAL AND CALCULATED STRAINS FOR CONCENTRATED LOAD APPLIED TO TRUSS AT JOINT 10 IN X_1X_2-DIRECTION

Truss	Member	Experimental						Calculated	
		ϵ_a	$\frac{\epsilon_b}{\epsilon_a}(100)$	ϵ_a	$\frac{\epsilon_b}{\epsilon_a}(100)$	ϵ_a	$\frac{\epsilon_b}{\epsilon_a}(100)$	ϵ_a	$\frac{\epsilon_b}{\epsilon_a}(100)$
		P = 100 lbf	(445 N)	P = 200 lbf	(890 N)	P = 250 lbf	(1110 N)	P = 200 lbf	(890 N)
Welded aluminum	4-6	270×10^{-6}	10	536×10^{-6}	9	672×10^{-6}	9	543×10^{-6}	8
	4-7	-63	33	-128	36	160	37	-122	47
	6-9	-183	20	-366	23	-458	24	-365	23
	8-9	-323	9	-650	9	-811	9	-621	9
	7-10	-299	26	-596	26	-743	26	-595	22
		P = 100 lbf	(445 N)	P = 200 lbf	(890 N)	P = 225 lbf	(1000 N)	P = 200 lbf	(890 N)
Bonded aluminum	1-6	-232×10^{-6}	14	-454×10^{-6}	16	-509×10^{-6}	16	-460×10^{-6}	8
	2-4	162	17	331	15	372	19	335	8
	6-9	-157	23	-304	25	339	29	-313	15
	7-9	227	--	461	--	515	--	466	6
	7-10	-341	21	-674	23	-761	24	-689	20
	8-10	462	10	922	8	1031	7	947	13
		P = 100 lbf	(445 N)	P = 200 lbf	(890 N)	P = 225 lbf	(1000 N)	P = 200 lbf	(890 N)
Bonded Be-38Al	4-5	-167×10^{-6}	3	-335×10^{-6}	4	-374×10^{-6}	4	-335×10^{-6}	2
	7-9	177	5	358	3	405	6	357	5
	7-10	-266	8	-536	11	-599	11	-535	14
	8-10	320	12	652	10	732	9	651	9
		P = 100 lbf	(445 N)	P = 200 lbf	(890 N)	P = 225 lbf	(1000 N)	P = 200 lbf	(890 N)
Bonded beryllium	2-4	79×10^{-6}	8	158×10^{-6}	6	181×10^{-6}	6	157×10^{-6}	6
	6-9	-75	--	-151	--	-167	--	-153	11
	7-9	80	7	162	7	186	7	162	5
	7-10	-145	--	-306	--	-327	--	-318	14

TABLE VIII.- SUMMARY OF TRUSS CONFIGURATION SELECTION STUDIES

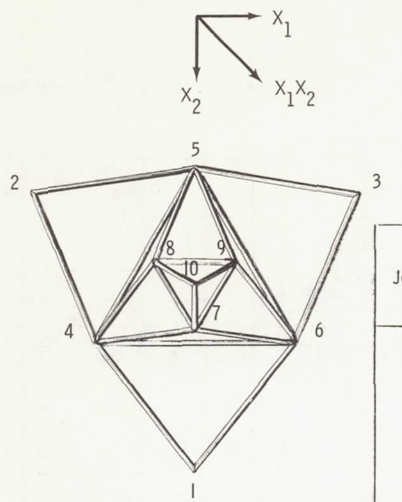
Truss (see fig. 12)	Number of legs	Number of joints	Number of members	Truss-member material	Loading condition	Member mass		Total truss mass	
						lbm	kg	lbm	kg
1	3	10	21	Aluminum	Single mass	1.79	0.81	4.39	2.00
					Multiple mass	2.16	0.98	4.75	2.16
				Beryllium	Single mass	0.79	0.36	3.39	1.54
					Multiple mass	0.89	0.40	3.49	1.58
2a	3	10	21	Aluminum	Single mass	1.49	0.68	4.09	1.86
					Multiple mass	2.45	1.11	5.05	2.29
				Beryllium	Single mass	0.65	0.30	3.25	1.47
					Multiple mass	1.06	0.48	3.66	1.66
2b	3	10	21	Aluminum	Single mass	1.41	0.64	4.01	1.82
				Beryllium	Single mass	0.67	0.30	3.27	1.48
3	4	13	29	Aluminum	Single mass	2.13	0.97	5.68	2.58
				Beryllium	Single mass	0.98	0.45	4.53	2.06
4	4	13	28	Aluminum	Single mass	2.04	0.93	5.49	2.49
				Beryllium	Single mass	0.91	0.41	4.36	1.98
5	4	13	28	Aluminum	Single mass	1.80	0.82	5.25	2.38
					Multiple mass	2.81	1.28	6.26	2.84
				Beryllium	Multiple mass	1.22	0.55	4.67	2.12

TABLE IX.- MATERIAL PROPERTIES USED FOR TRUSS DESIGN

Material	ρ		E		σ_y	
	lbm/in^3	Mg/m^3	psi	GN/m^2	ksi	MN/m^2
6061-T6 aluminum	0.098	2.71	10.0×10^6	69	34	234
As-extruded Be-38Al	0.075	2.08	28.0×10^6	193	75	517
Beryllium	0.067	1.85	40.0×10^6	276	40	276

TABLE X.- RANGE OF DIAMETERS FOR TRUSS COMPONENTS

Truss	Truss members		Joint clusters	
	in.	mm	in.	mm
Welded aluminum	0.25 to 0.75	6.35 to 19.05	----------	-----------
Bonded aluminum	0.31 to 0.88	7.87 to 22.35	0.31 to 0.88	7.87 to 22.35
Bonded Be-38Al	0.25 to 0.69	6.35 to 17.53	0.25 to 0.50	6.35 to 12.70
Bonded beryllium	0.25 to 0.56	6.35 to 14.22	0.25 to 0.50	6.35 to 12.70



Joint	Joint Coordinates					
	X_1		X_2		X_3	
	in.	mm	in.	mm	in.	m
1	0.00	0.0	16.10	408.9	0.00	0.000
2	-13.94	-354.1	-8.05	-204.5	0.00	0.000
3	13.94	354.1	-8.05	-204.5	0.00	0.000
4	-8.71	-221.2	5.03	127.8	24.00	0.610
5	0.00	0.0	-10.06	-255.5	24.00	0.610
6	8.71	221.2	5.03	127.8	24.00	0.610
7	0.00	0.0	4.03	102.4	48.00	1.219
8	-3.49	-88.6	-2.01	-51.1	48.00	1.219
9	3.49	88.6	-2.01	-51.1	48.00	1.219
10	0.00	0.0	0.00	0.0	64.00	1.626

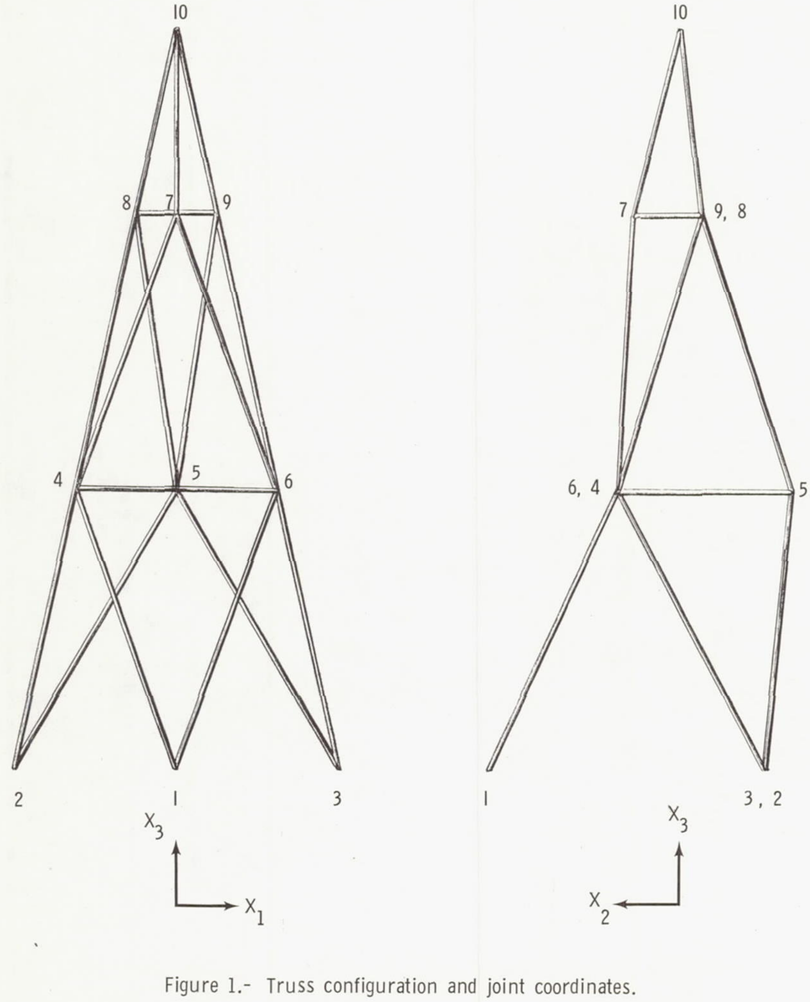
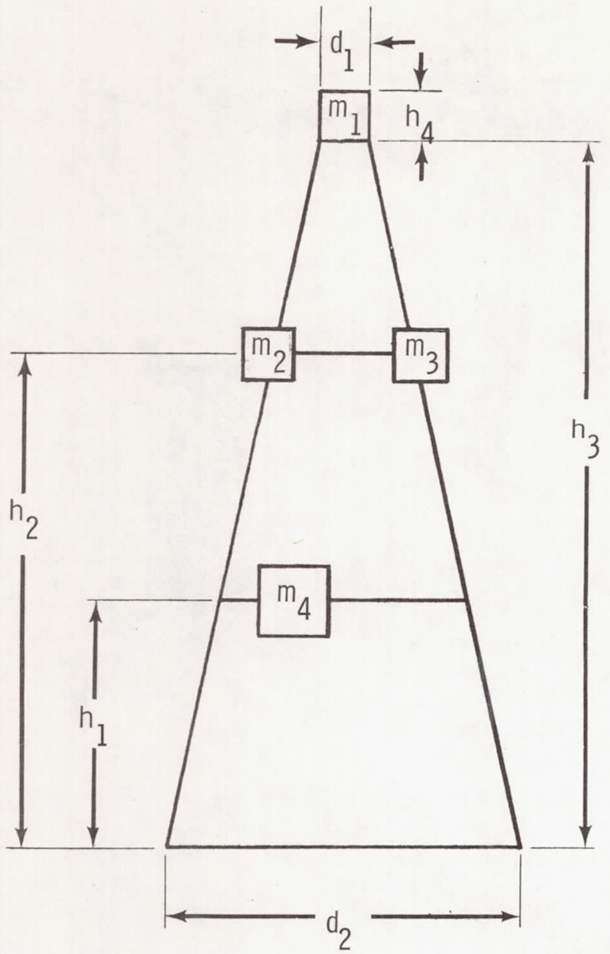


Figure 1.- Truss configuration and joint coordinates.



Experimental Package Mass Restraints:

1. m_1, m_2, and m_3, are 5.0-lbm (2.27-kg) masses.
2. m_4 is a 10-lbm (4.54-kg) mass.
3. m_2 and m_3 must have the same elevation.
4. m_4 must not lie in the plane perpendicular to the base which contains m_2 and m_3.

Dimension	Maximum		Minimum	
	in.	m	in.	m
h_1	24	0.610	18	0.457
h_2	50	1.270	30	0.762
h_3	72	1.830	60	1.525
h_4	12	0.307	--	-----
d_1	18	0.457	--	-----
d_2	36	0.915	24	0.610

Figure 2.- Truss-configuration envelope and experimental-package restraints.

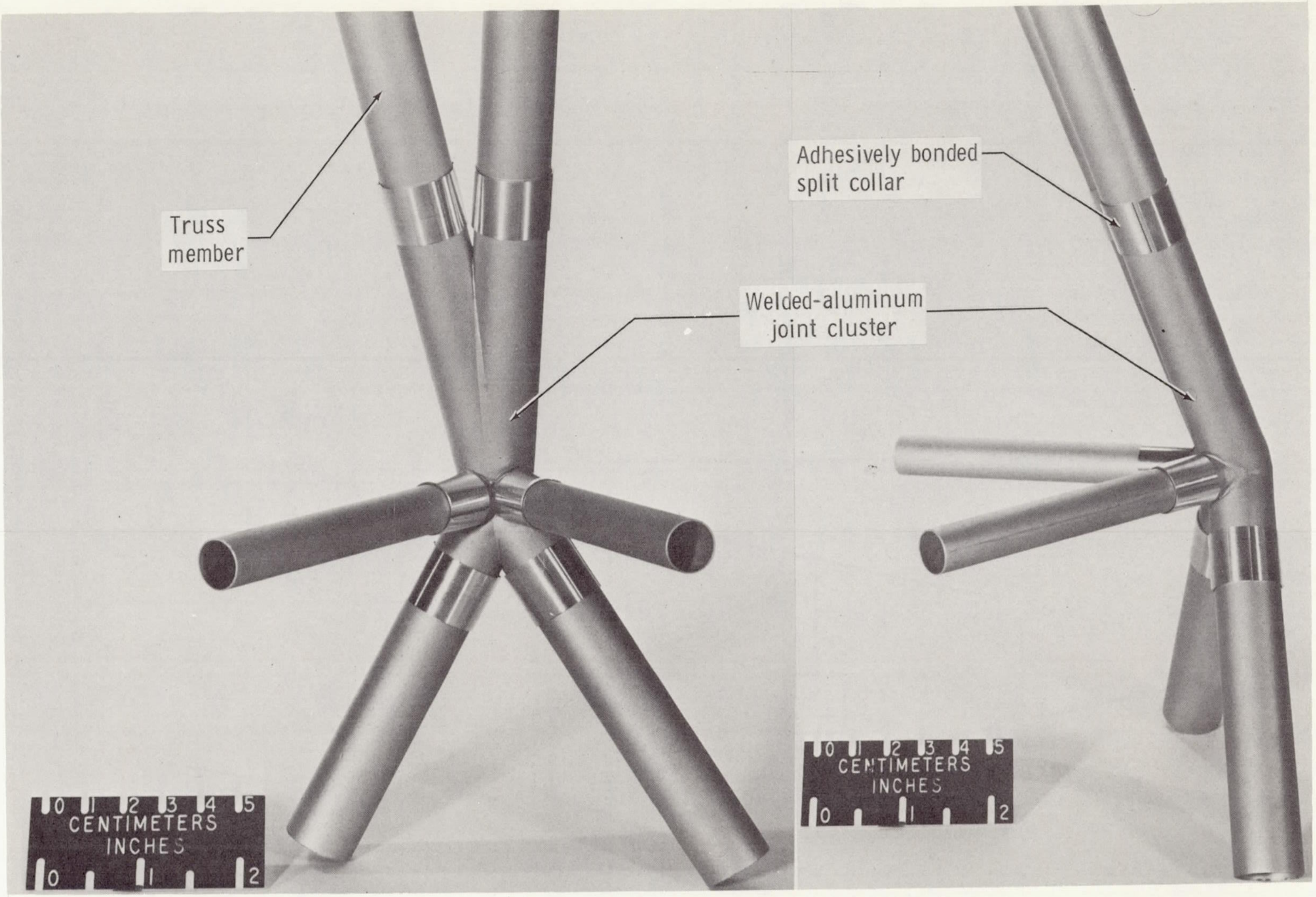
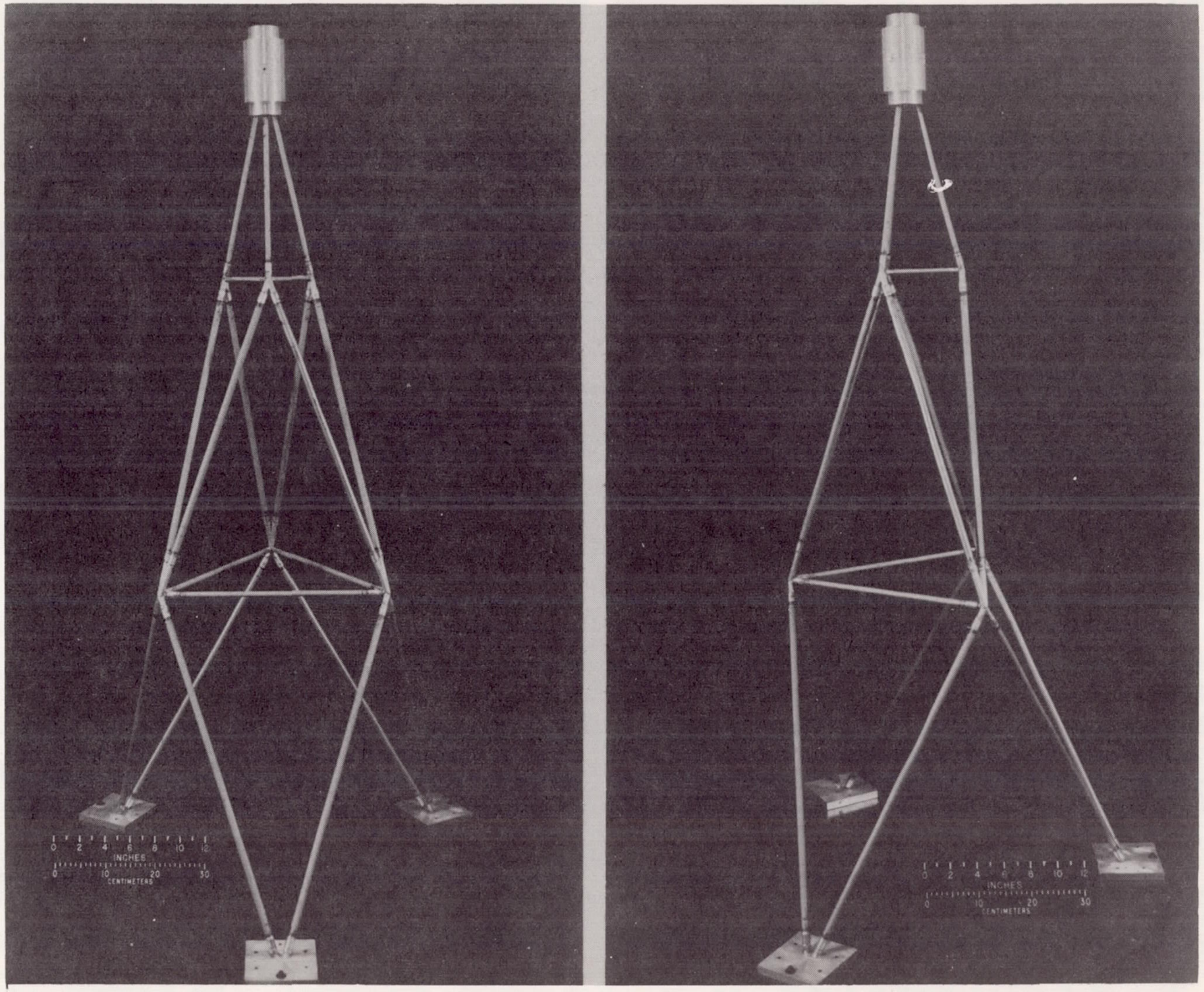


Figure 3.- Joint configuration selected for bonded trusses.

L-69-1326

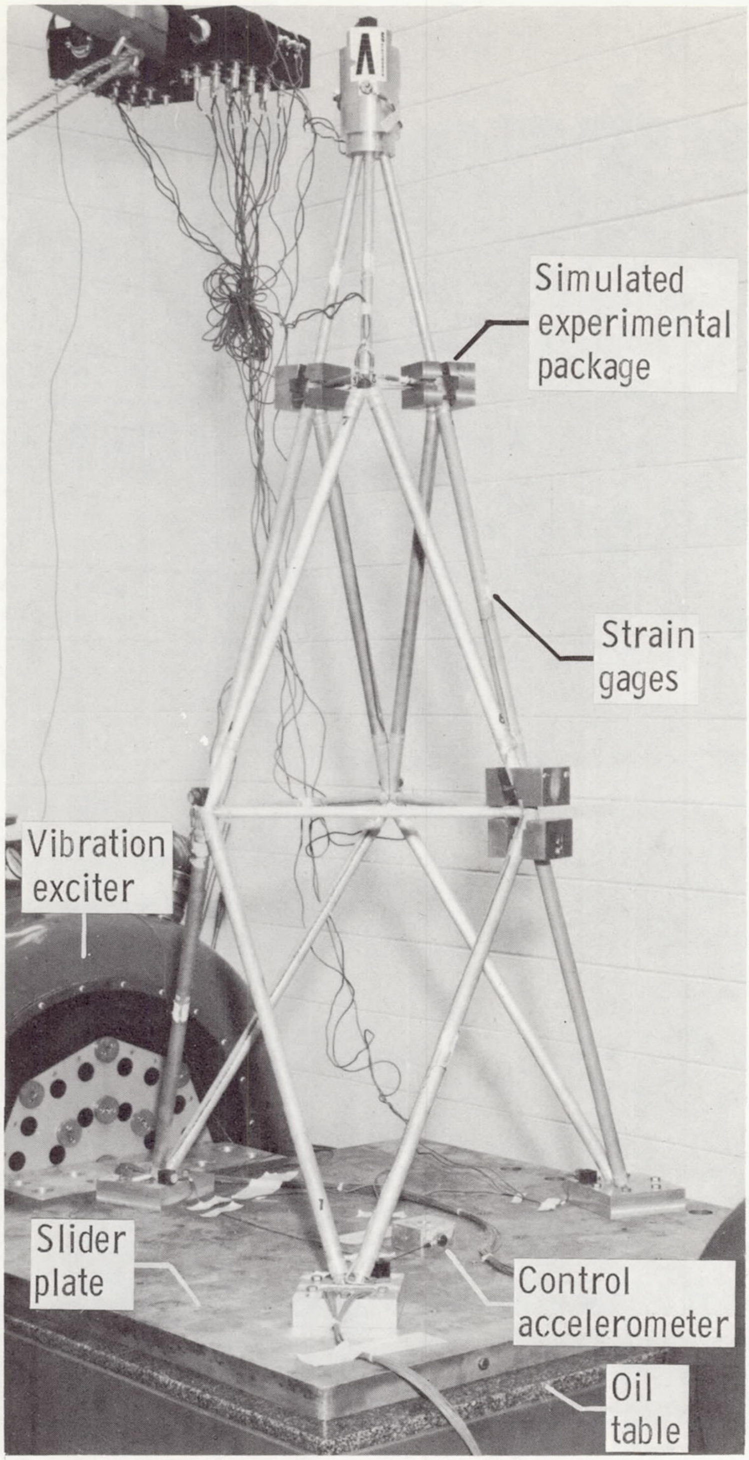


(a) Looking in $-X_2$-direction.

(b) Looking in X_1-direction.

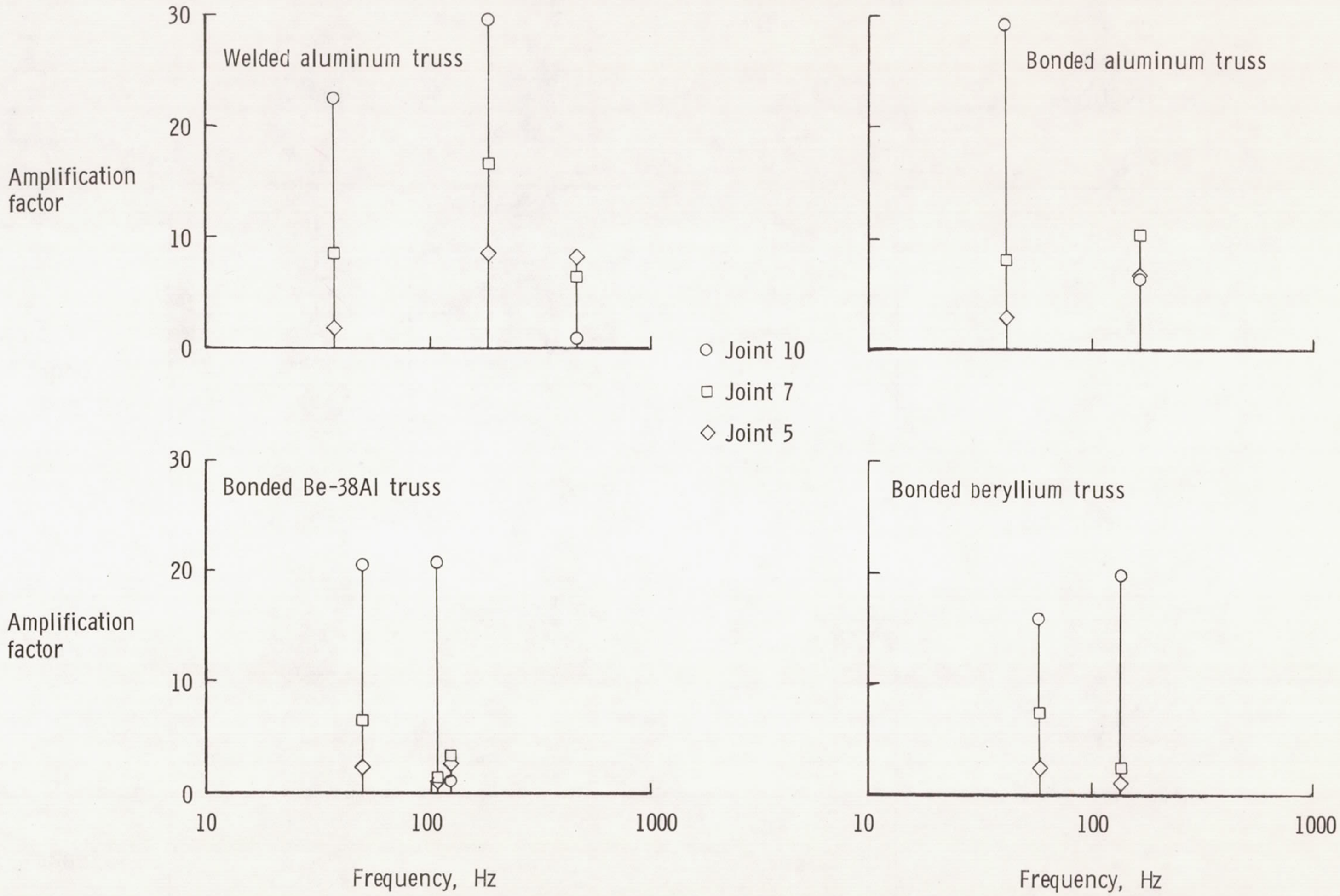
Figure 4.- Bonded beryllium truss.

L-3042-1



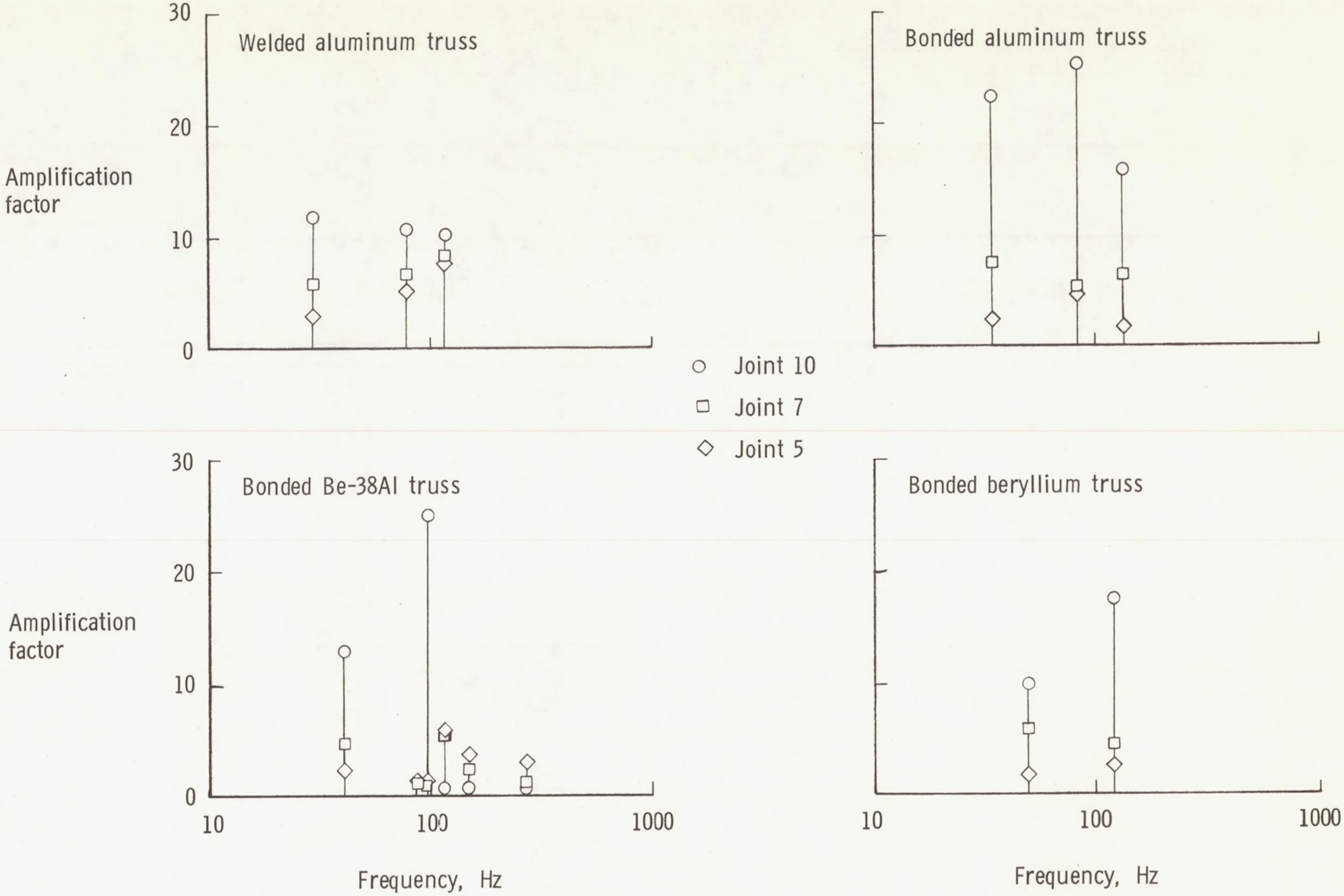
L-68-776.1

Figure 5.- Bonded aluminum truss in multiple-mass loading condition mounted for lateral vibration tests in X_1X_2-direction.



(a) Single-mass loading condition.

Figure 6.- Peak values of dynamic amplification as a function of excitation frequency. Truss joint responses for 1g peak input in X_1X_2-direction.



(b) Multiple-mass loading condition.

Figure 6.- Concluded.

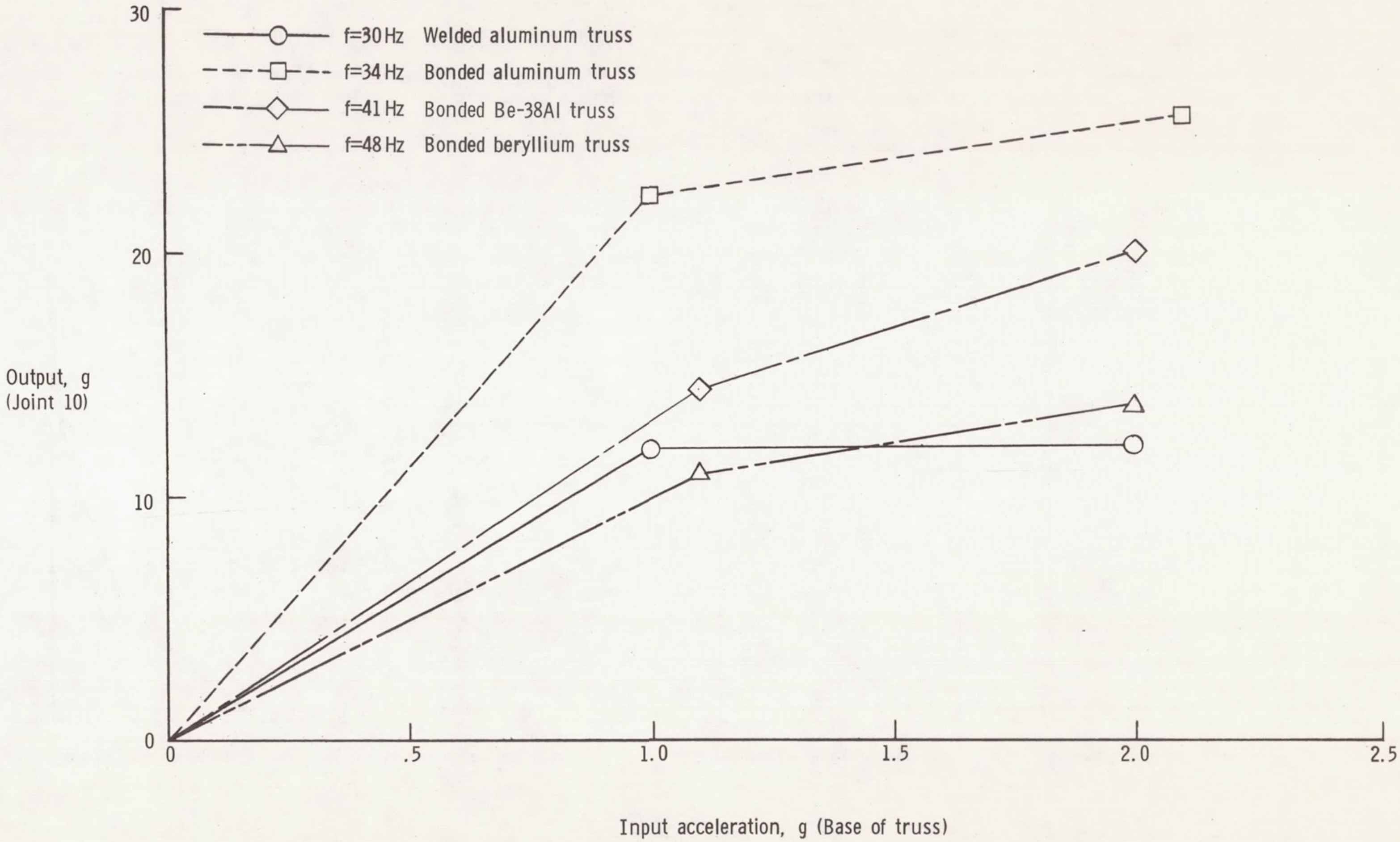
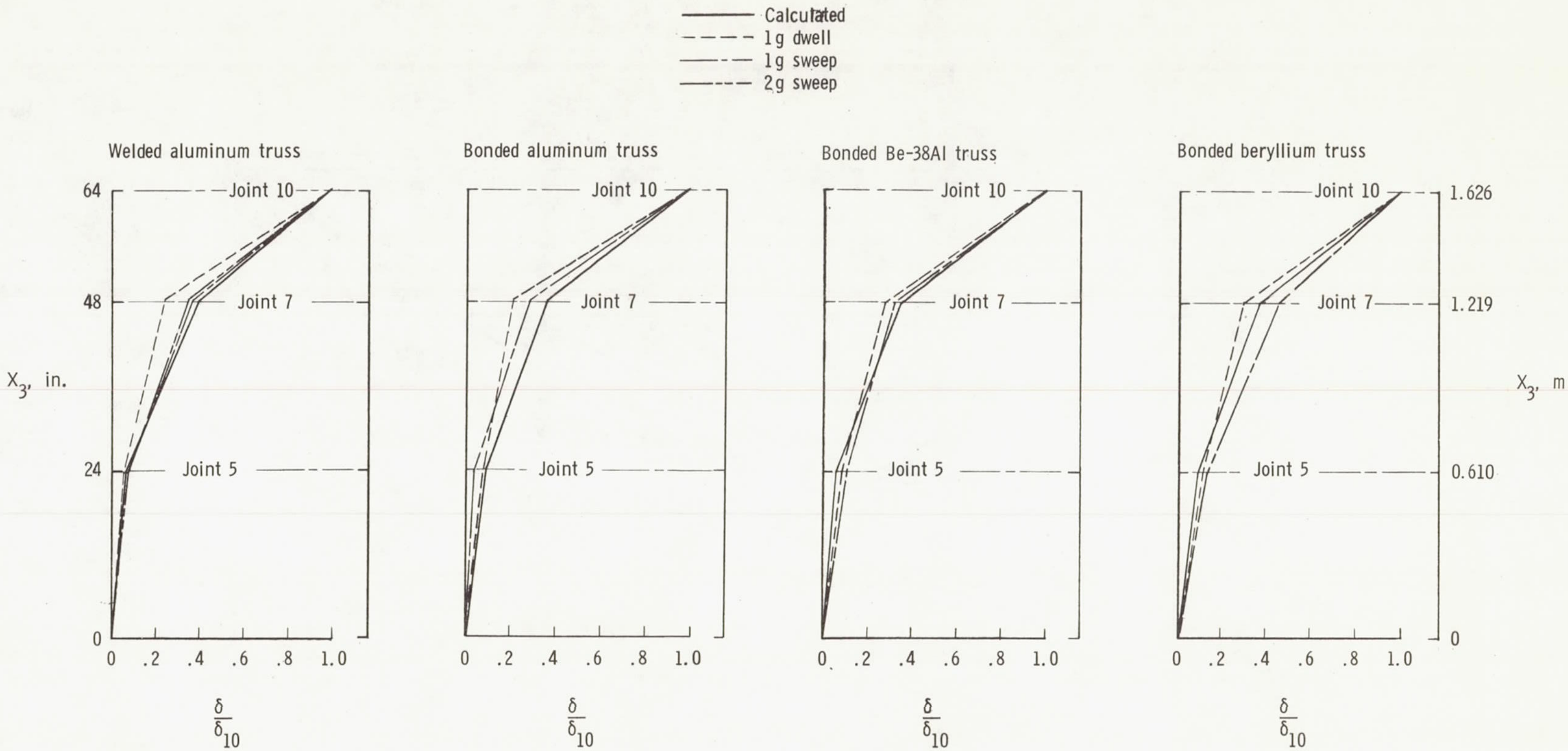
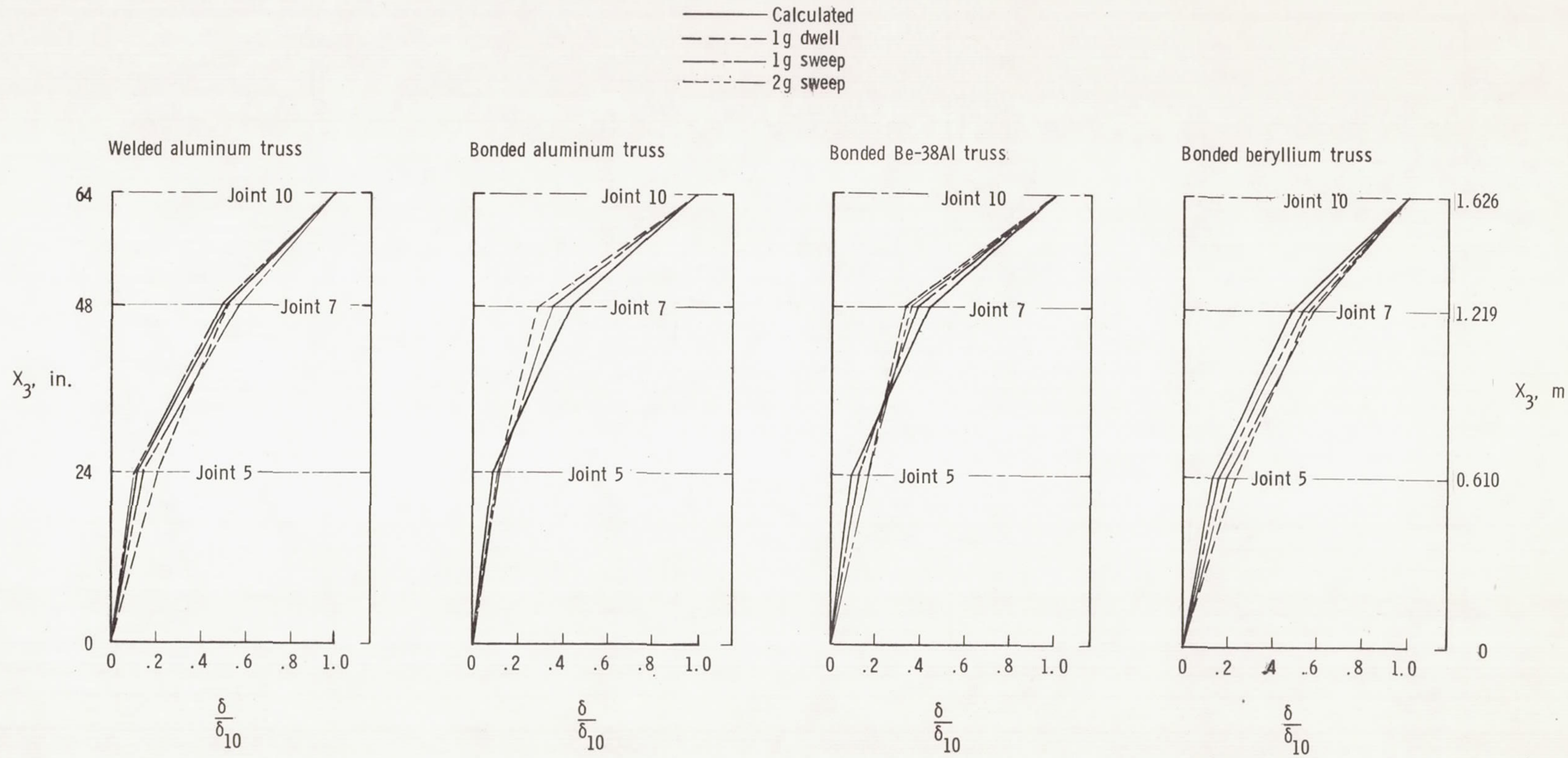


Figure 7.- Truss response to excitation in X_1X_2-direction. Multiple-mass loading condition.



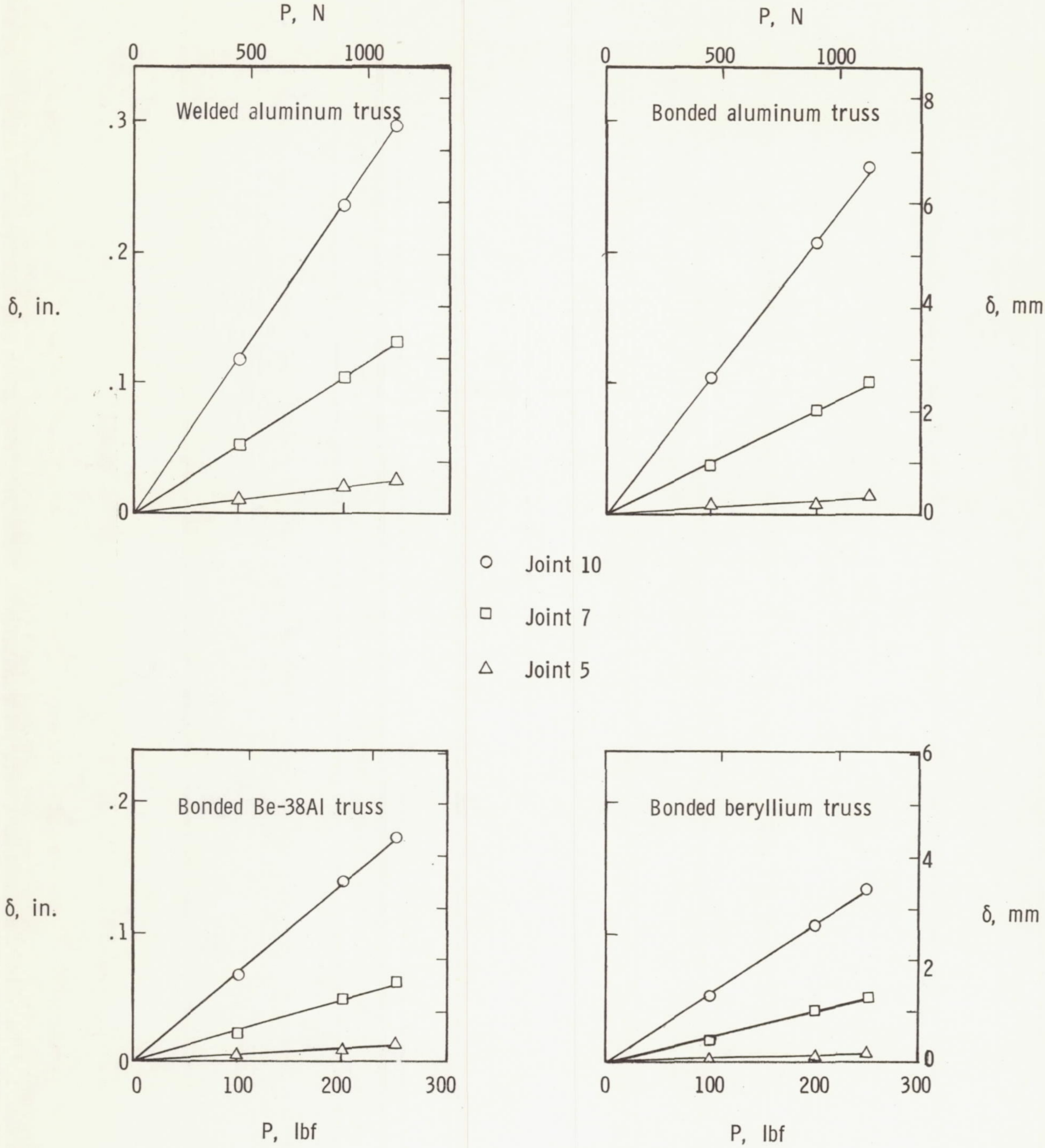
(a) Single-mass loading condition.

Figure 8.- Comparison between experimental and calculated first vibration mode for excitation in X_1X_2-direction.



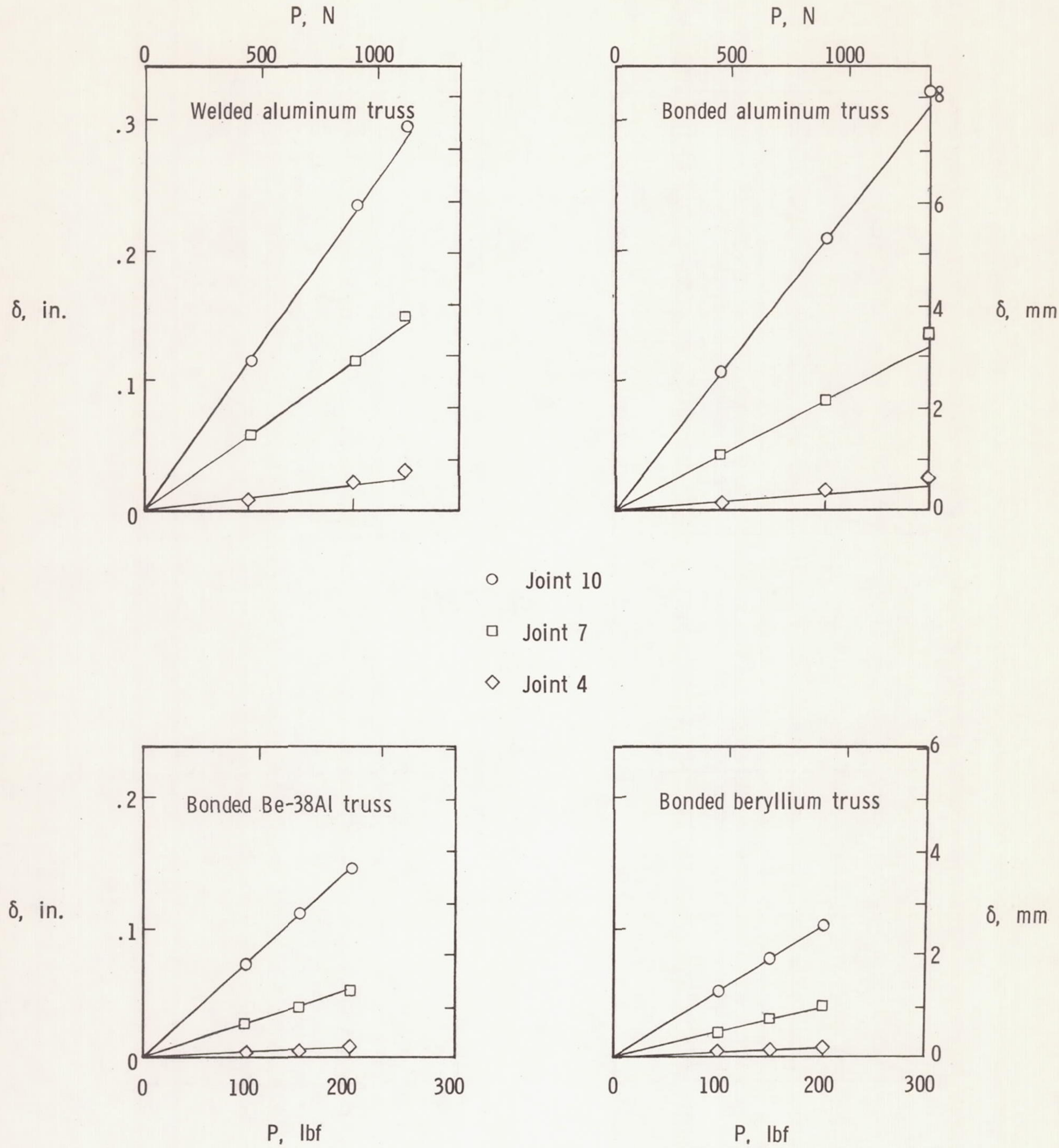
(b) Multiple-mass loading condition.

Figure 8.- Concluded.



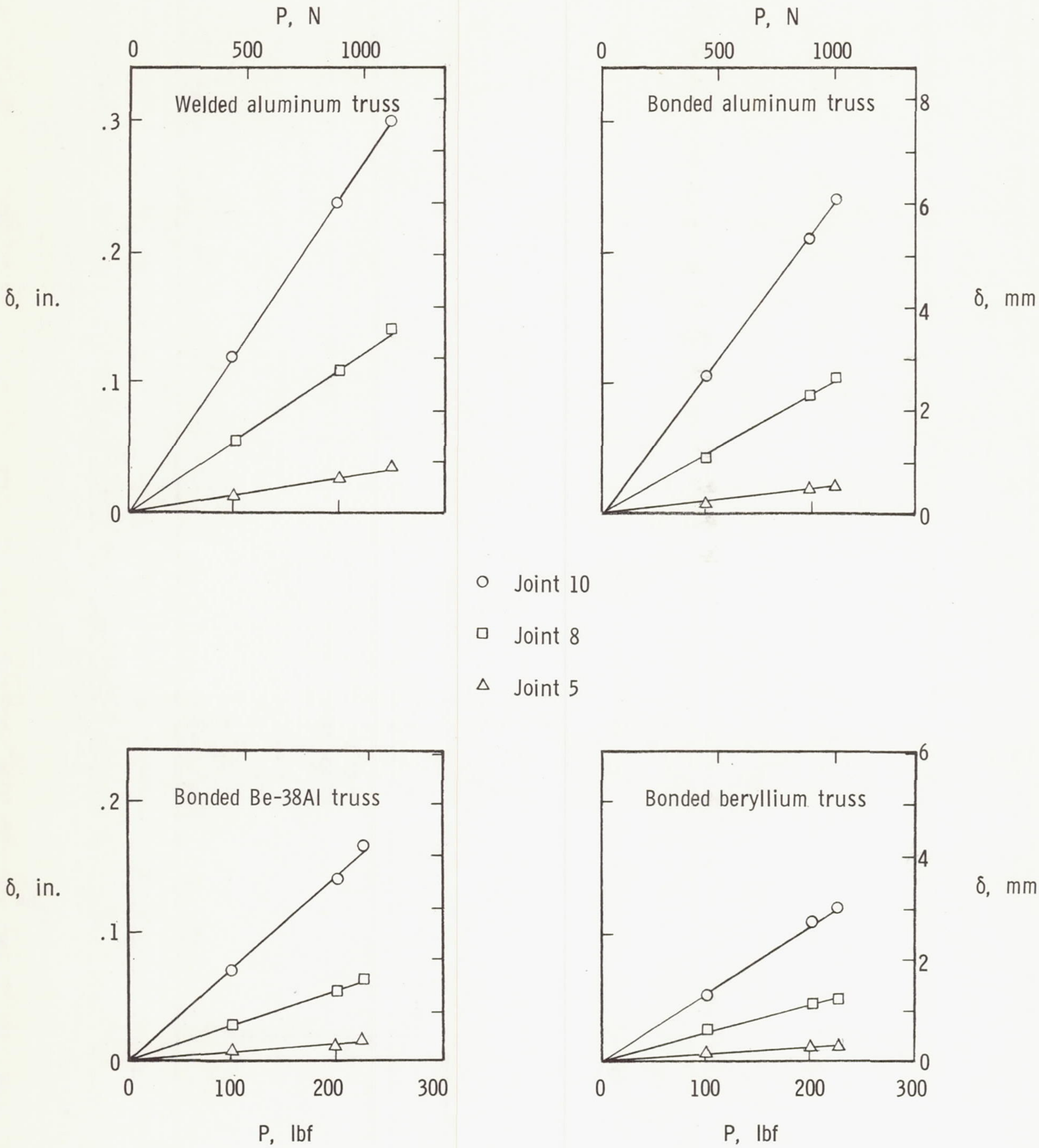
(a) Load in X_1-direction.

Figure 9.- Joint deflections for rapidly applied static load at joint 10.



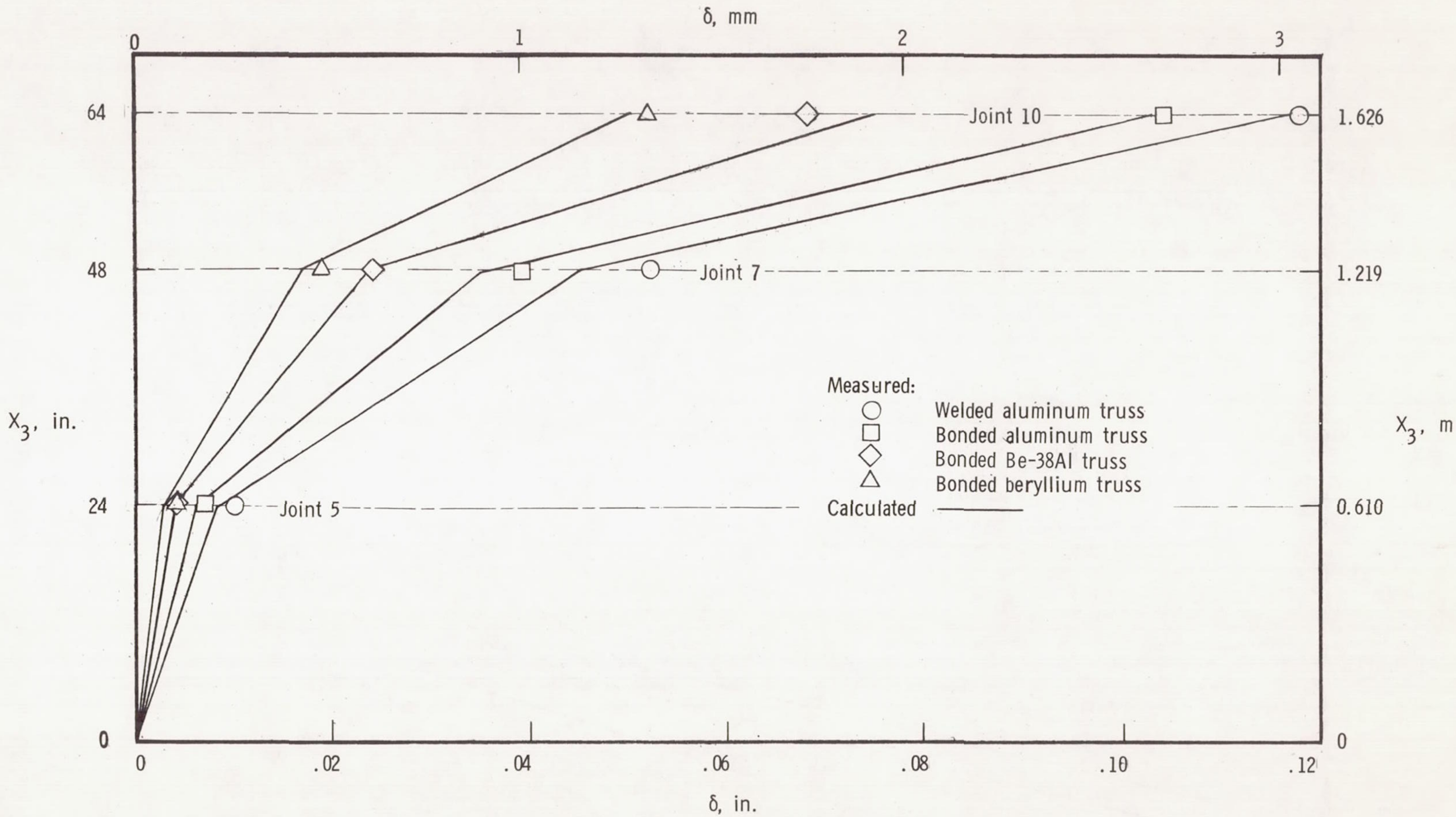
(b) Load in $-X_2$-direction.

Figure 9.- Continued.



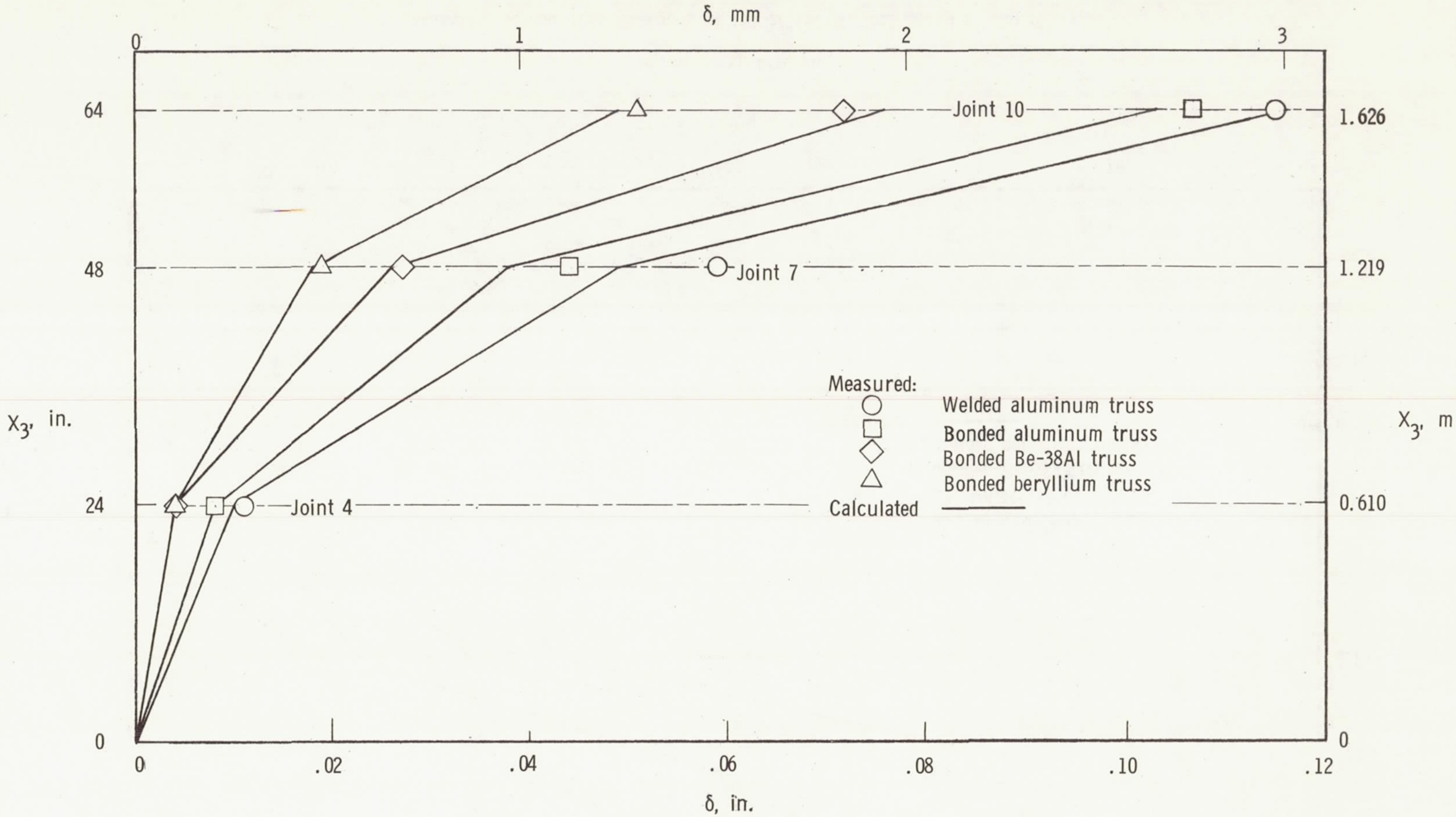
(c) Load in X_1X_2-direction.

Figure 9.- Concluded.



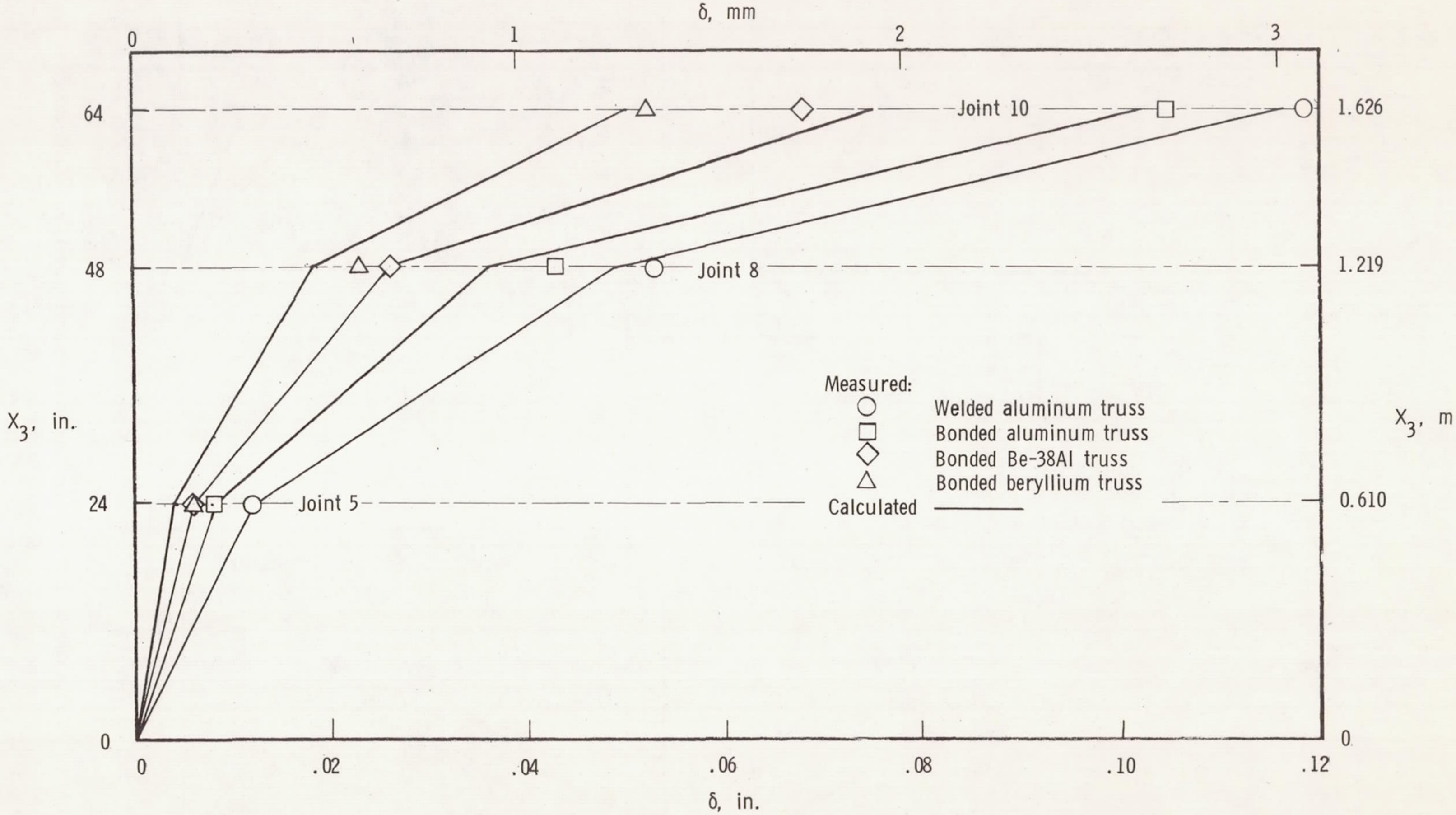
(a) Load in X_1-direction.

Figure 10.- Static truss deflections for 100 lbf (445 N) load applied at joint 10.



(b) Load in $-X_2$-direction.

Figure 10.- Continued.



(c) Load in X_1X_2-direction.

Figure 10.- Concluded.

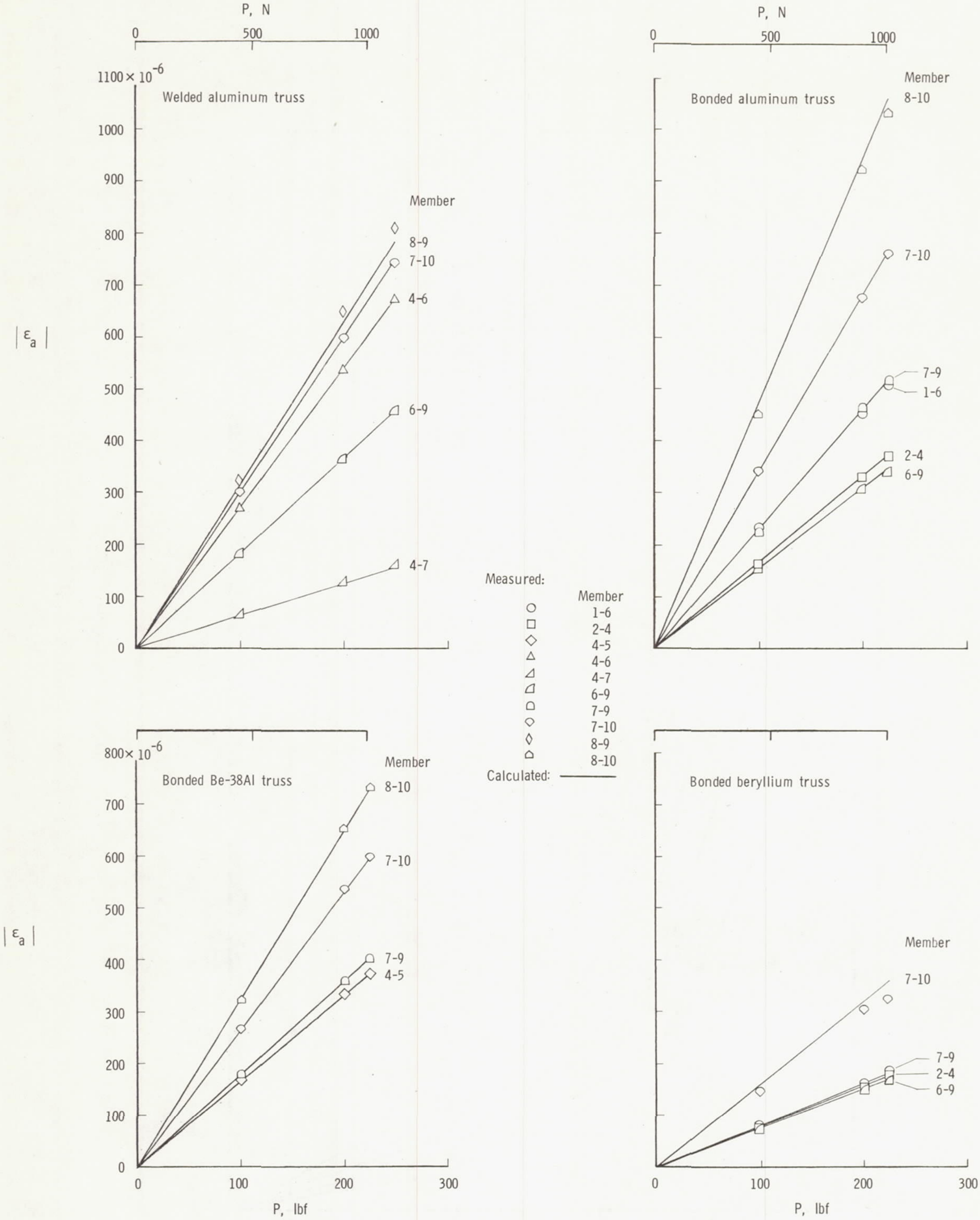


Figure 11.- Absolute value of axial strain for static loads applied at joint 10 in X_1X_2-direction.

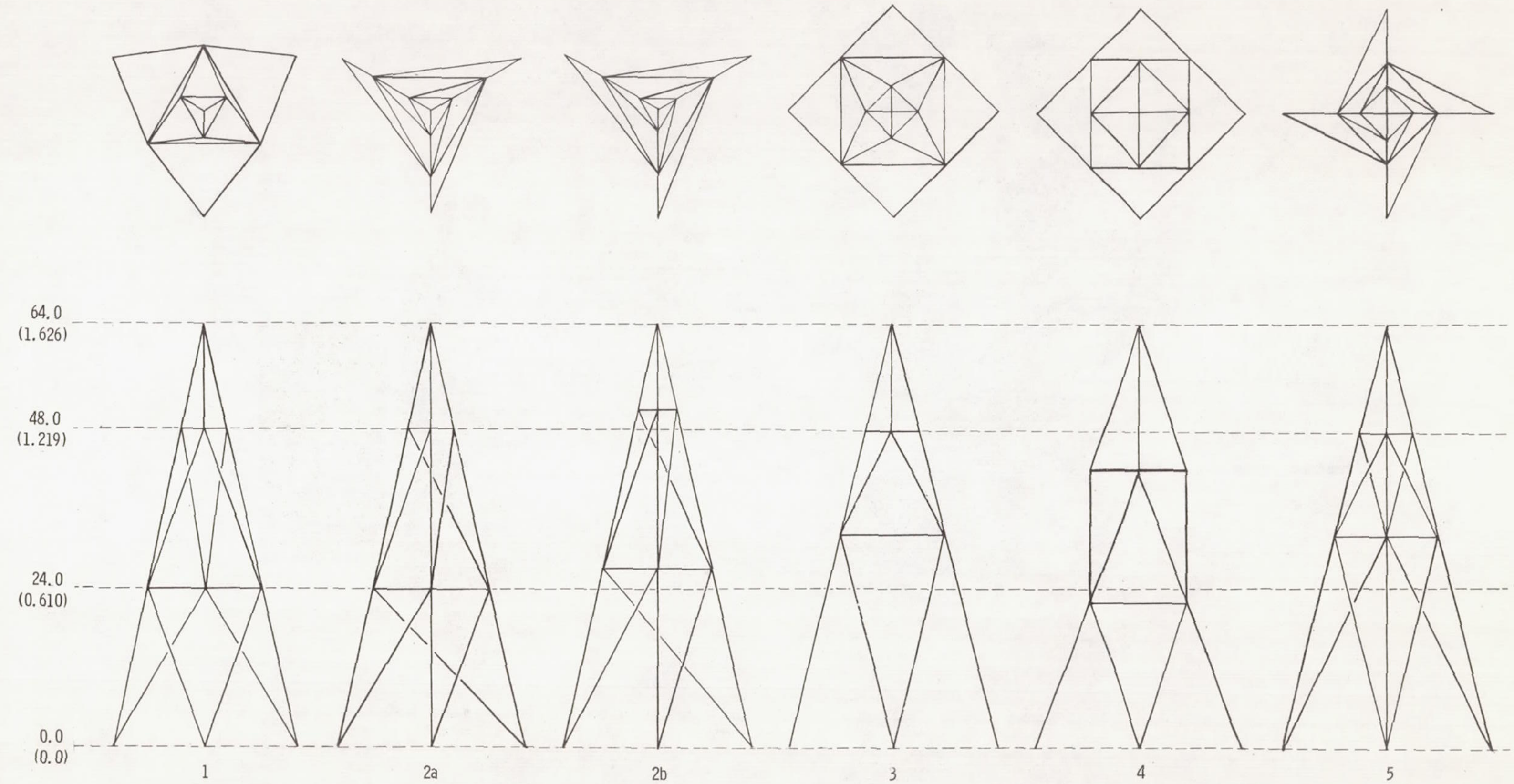
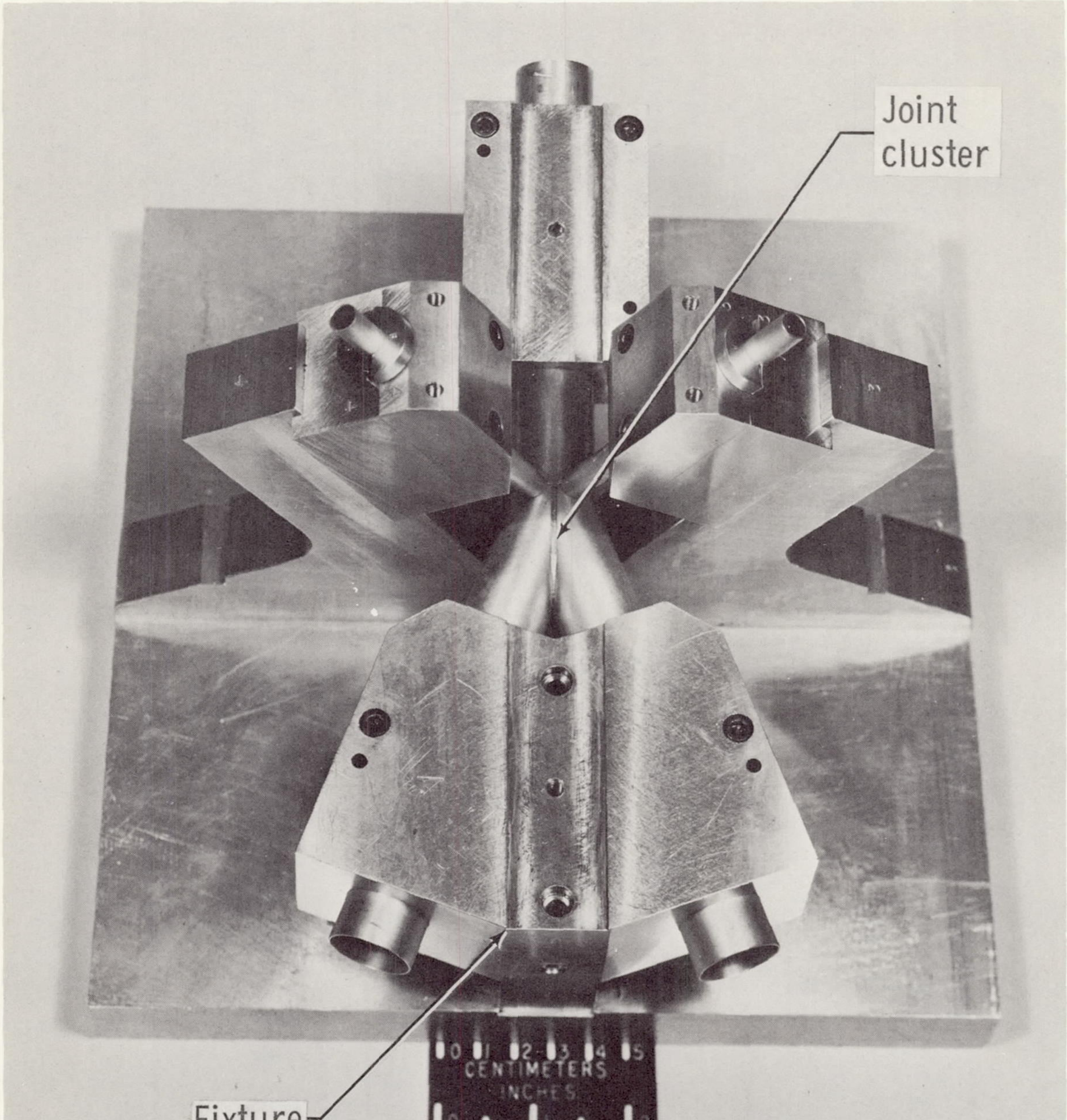
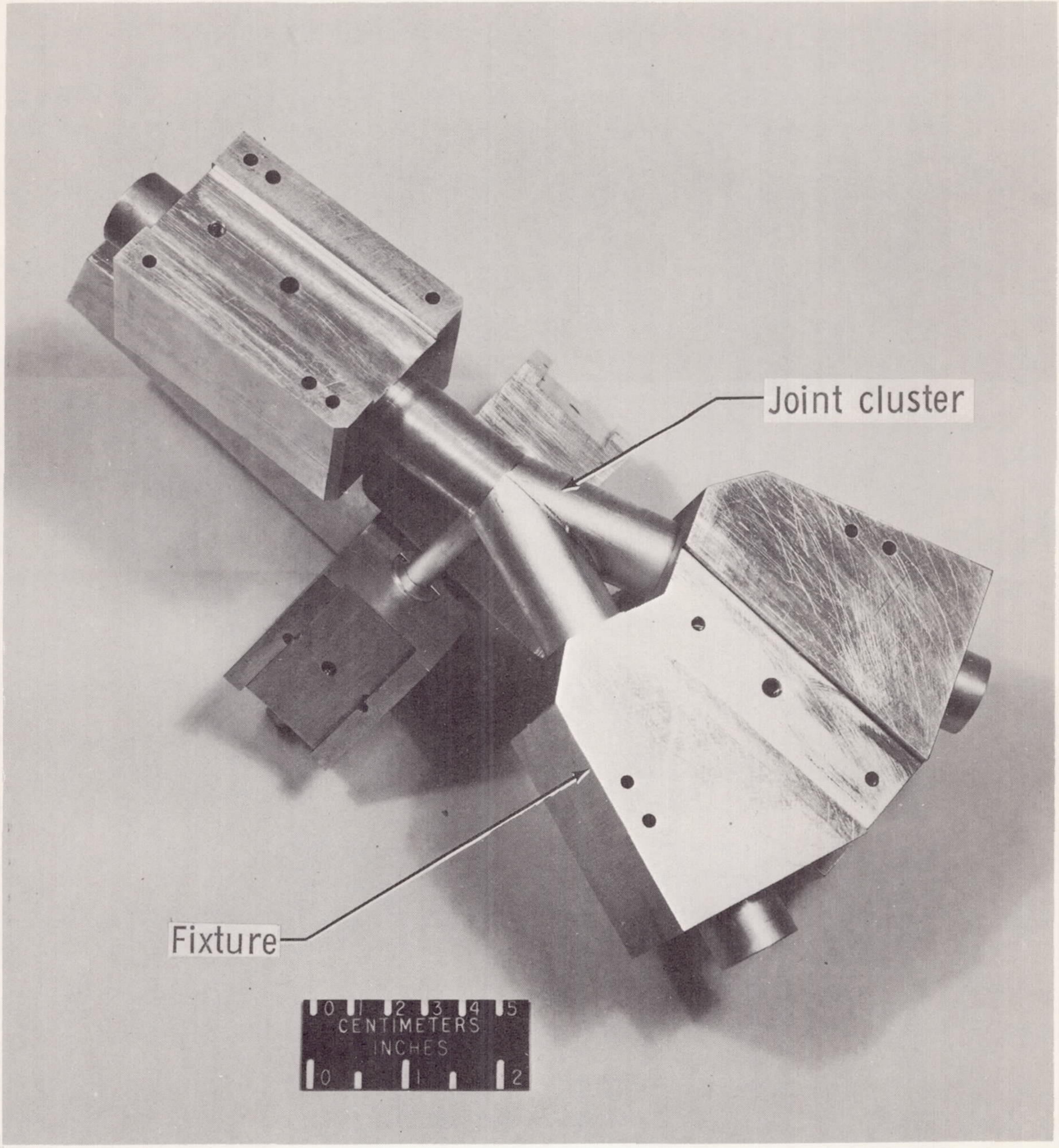


Figure 12.- Typical truss configurations. All base diameters are 32 inches (813 mm). (Dimensions are shown in inches and parenthetically in meters.)



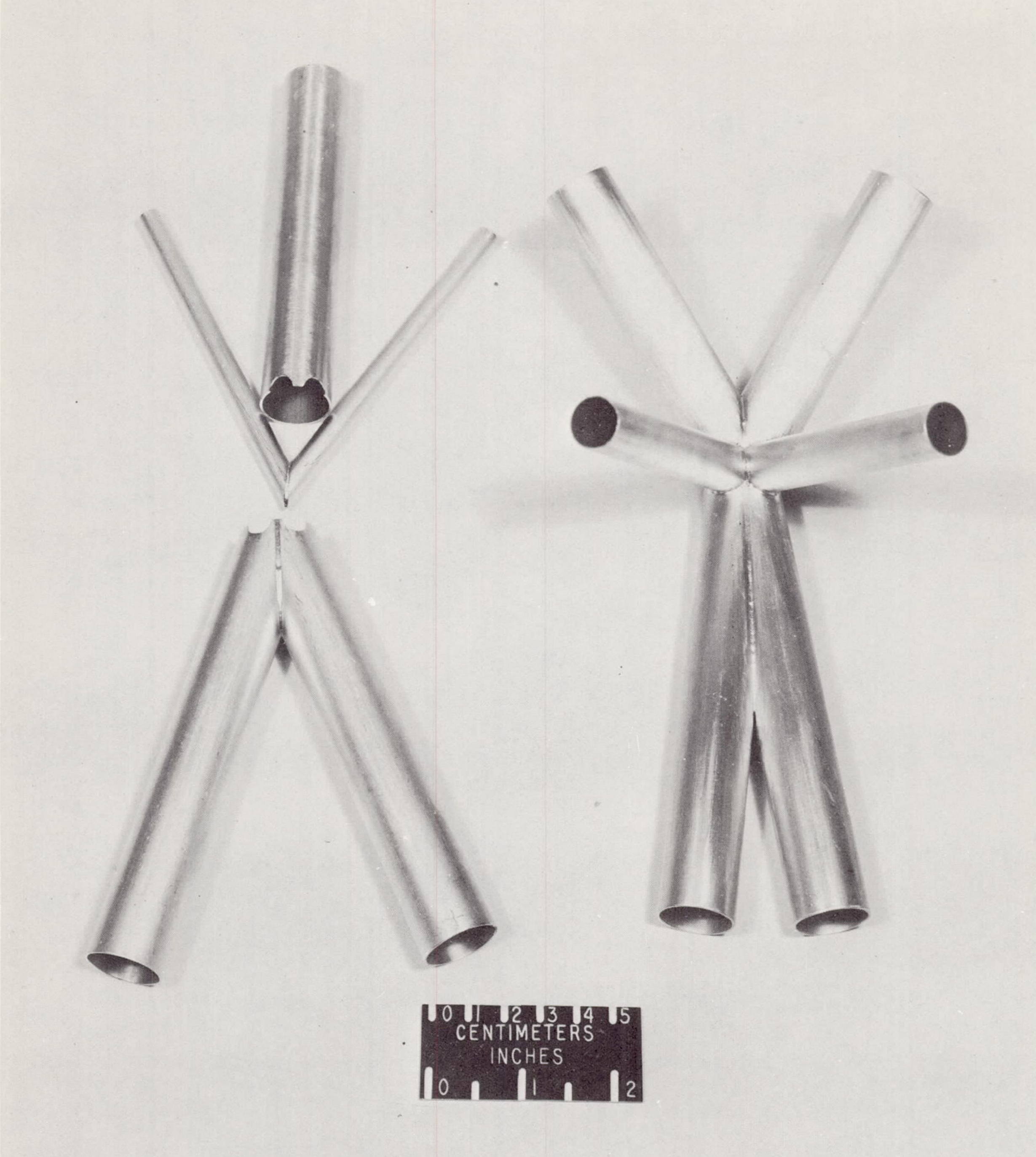
(a) Top view.

Figure 13.- Joint-cluster fabrication fixture. L-67-1938.1



(b) Bottom view.

Figure 13.- Concluded. L-67-1936.1



(a) Before final welding sequence. Joint 7.

(b) After final welding sequence. Joint 5.

Figure 14.- Joint-cluster fabrication sequence.

L-67-1939

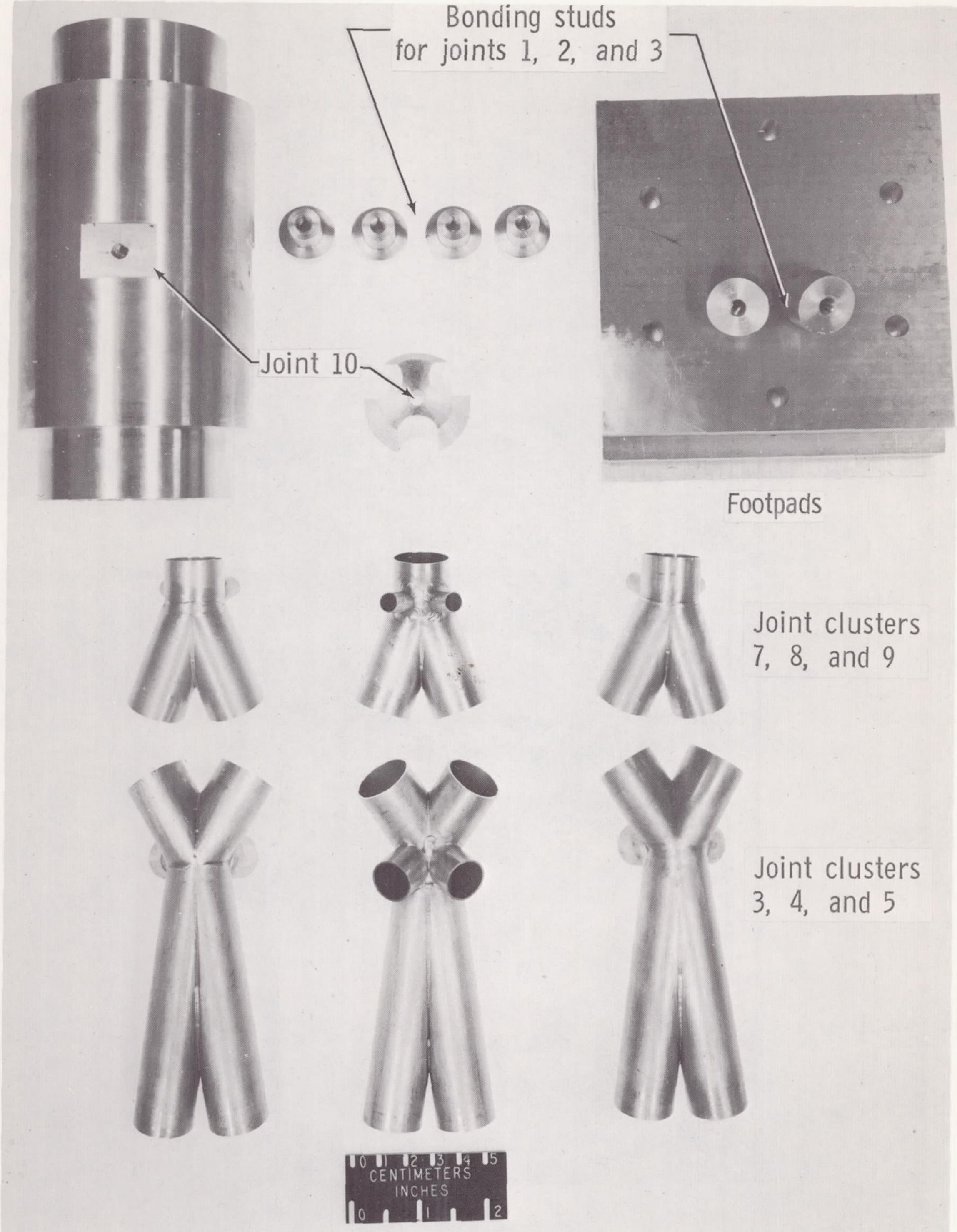
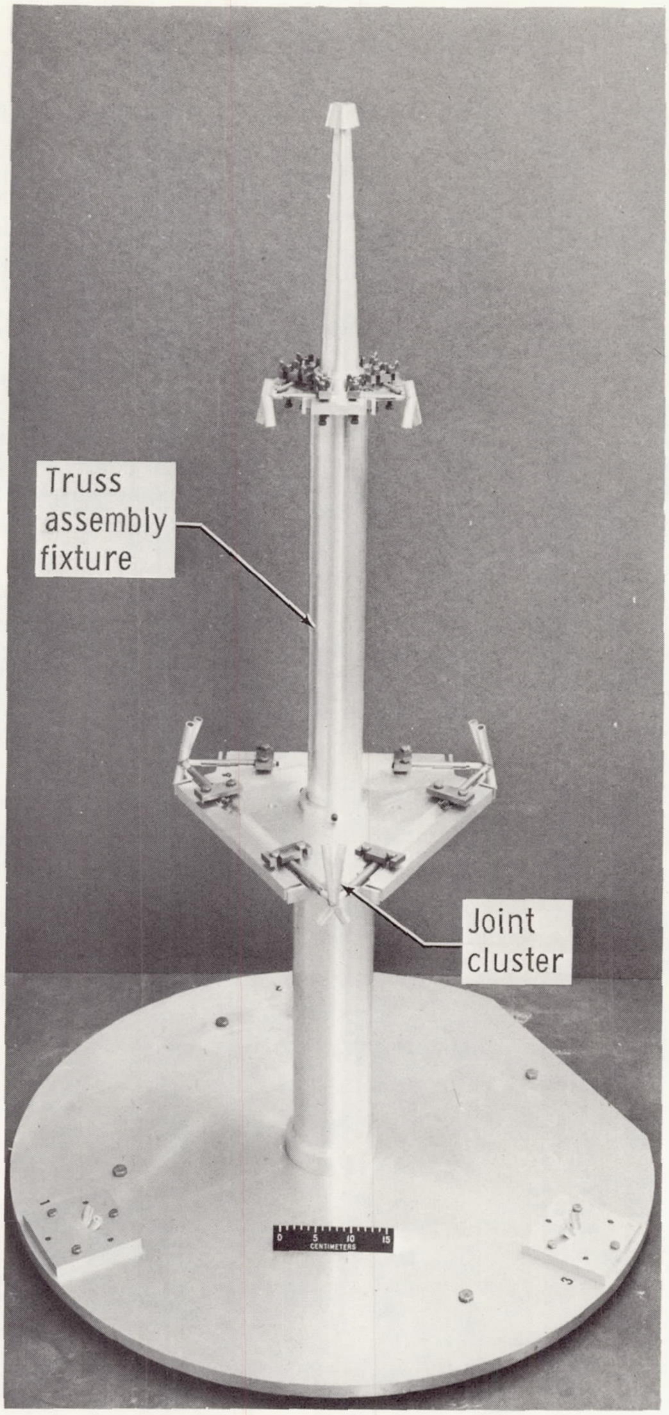
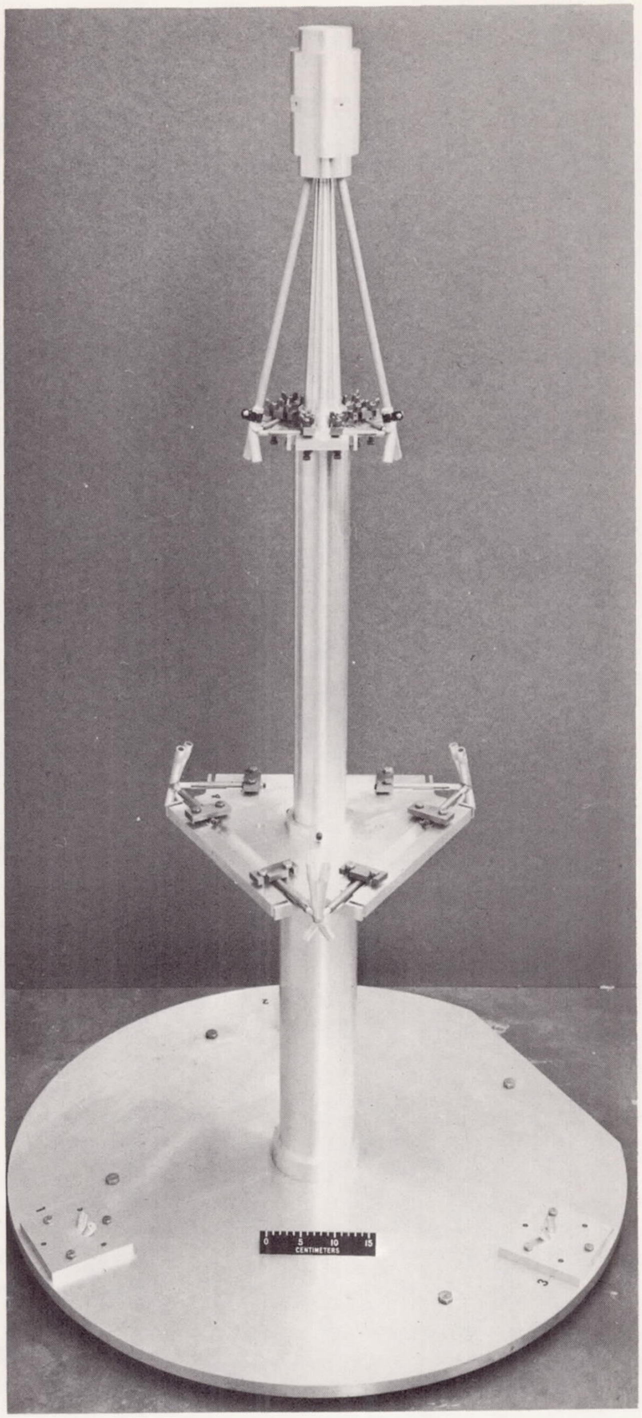


Figure 15.- Joint components for bonded aluminum truss. L-68-7402.1



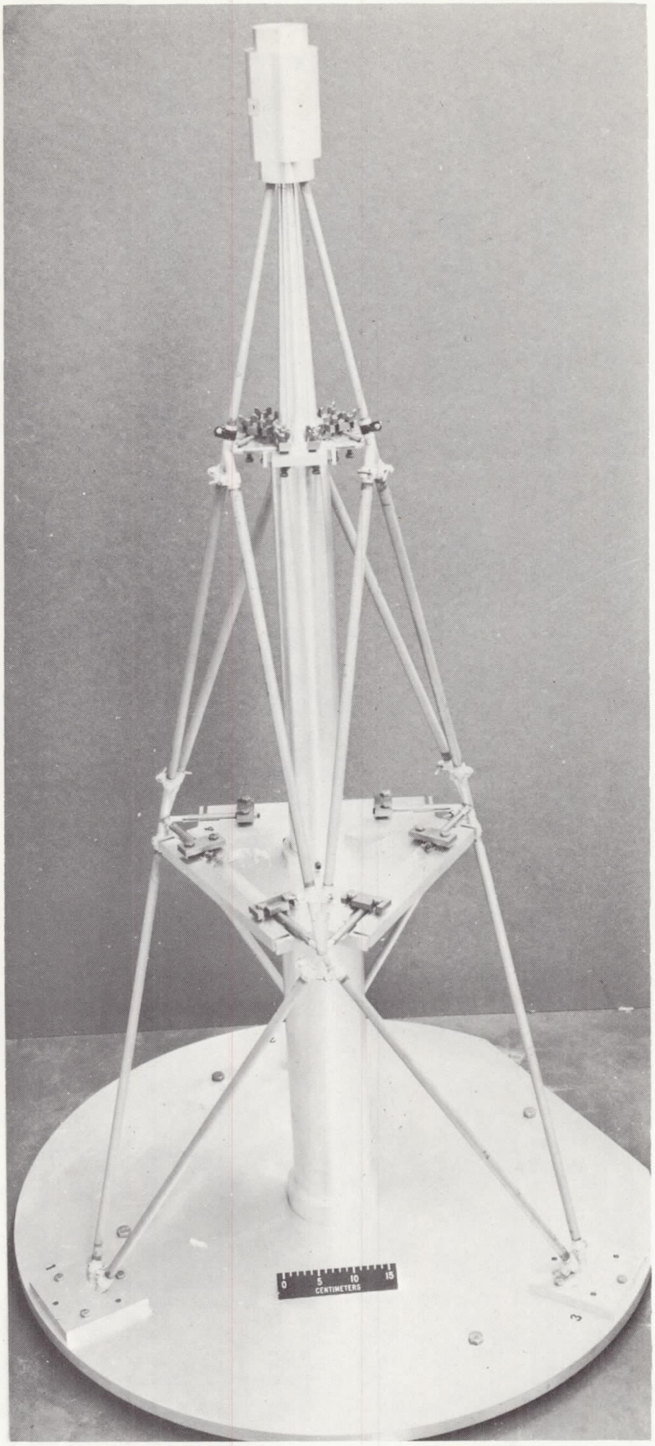
(a) Initial joint-cluster location.

Figure 16.- Bonded-truss assembly sequence. L-68-2808.1



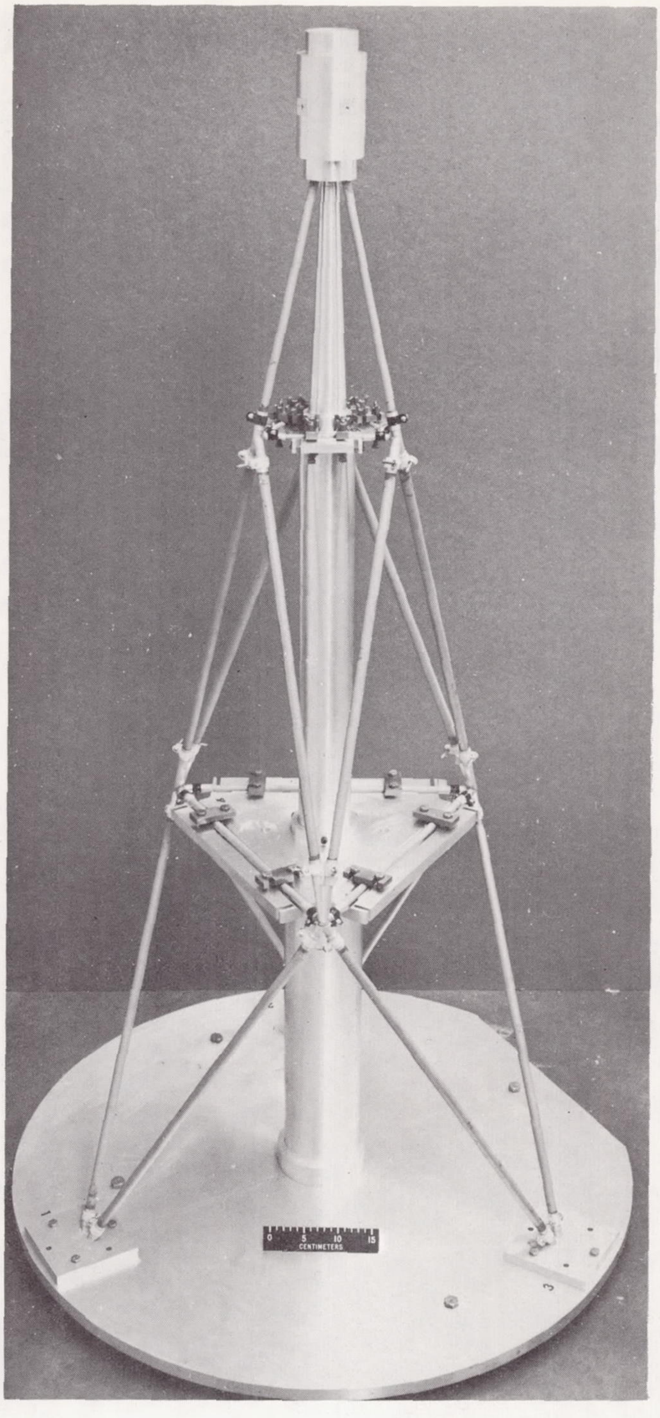
(b) Top tier bonded.

Figure 16.- Continued. L-68-2807



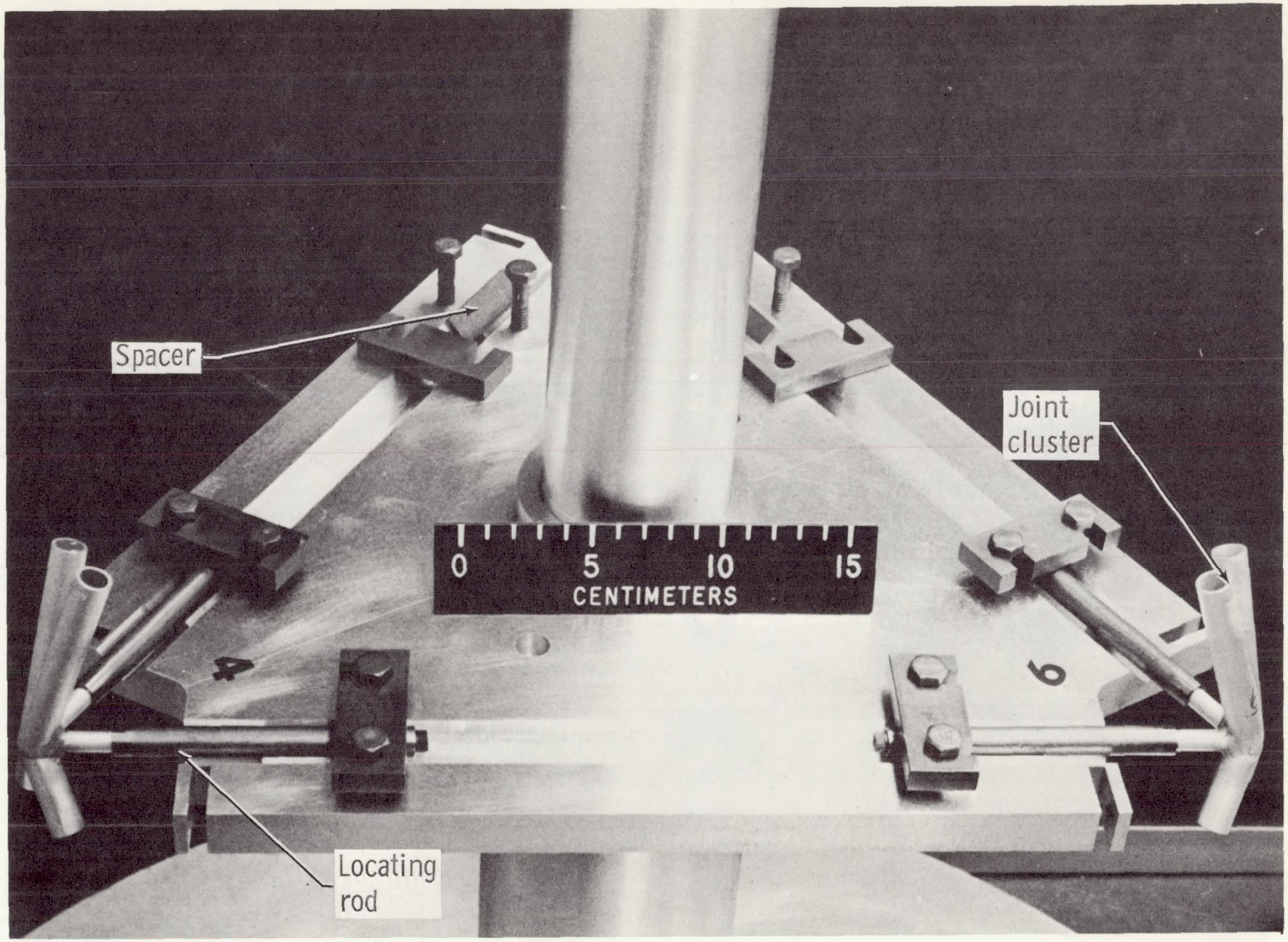
(c) Bonding of vertical truss members complete.

Figure 16.- Continued. L-68-2805



(d) Truss bonding complete.

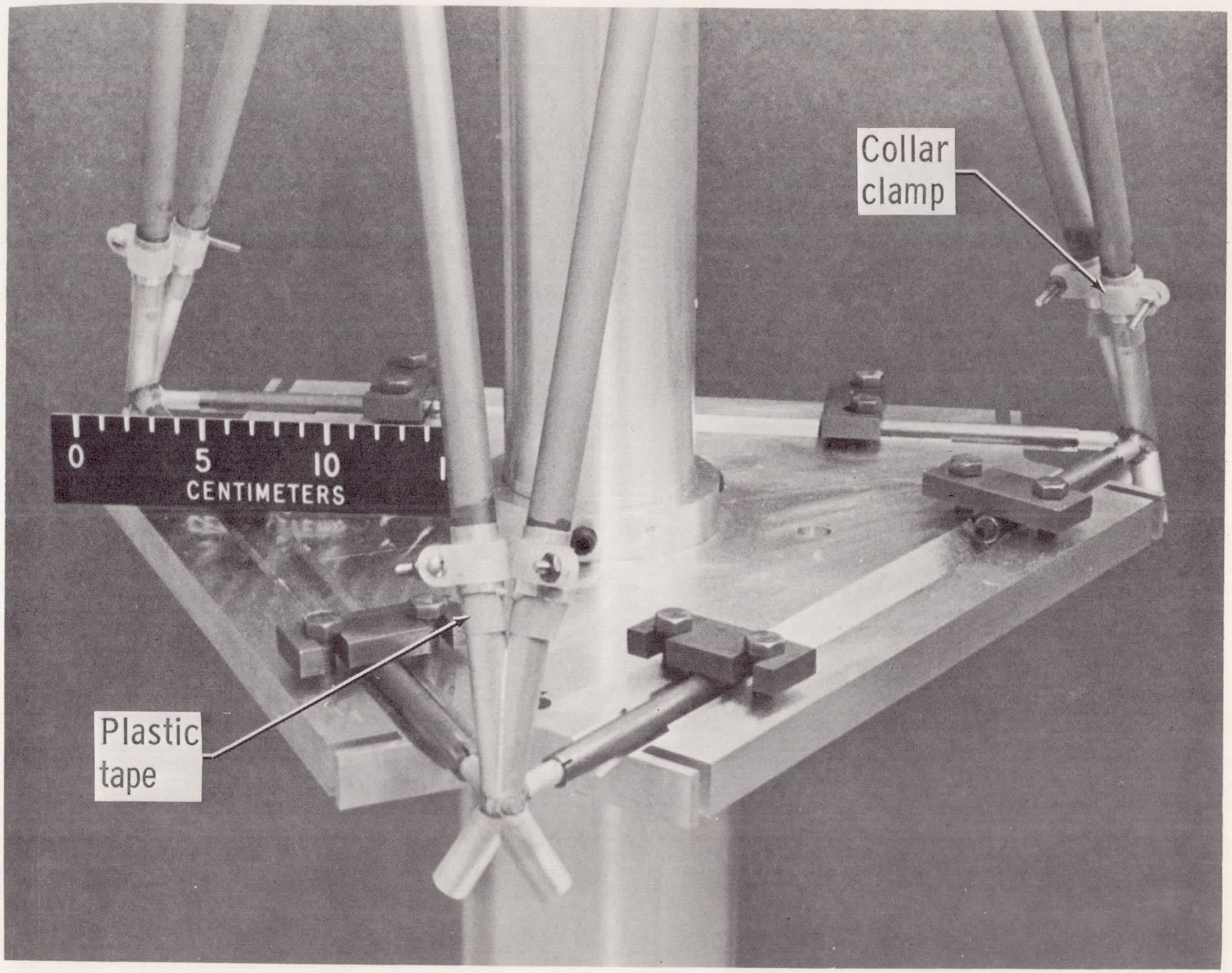
Figure 16.- Concluded. L-68-2804



(a) Joint-cluster location.

Figure 17.- Details of joint-cluster bonding sequence.

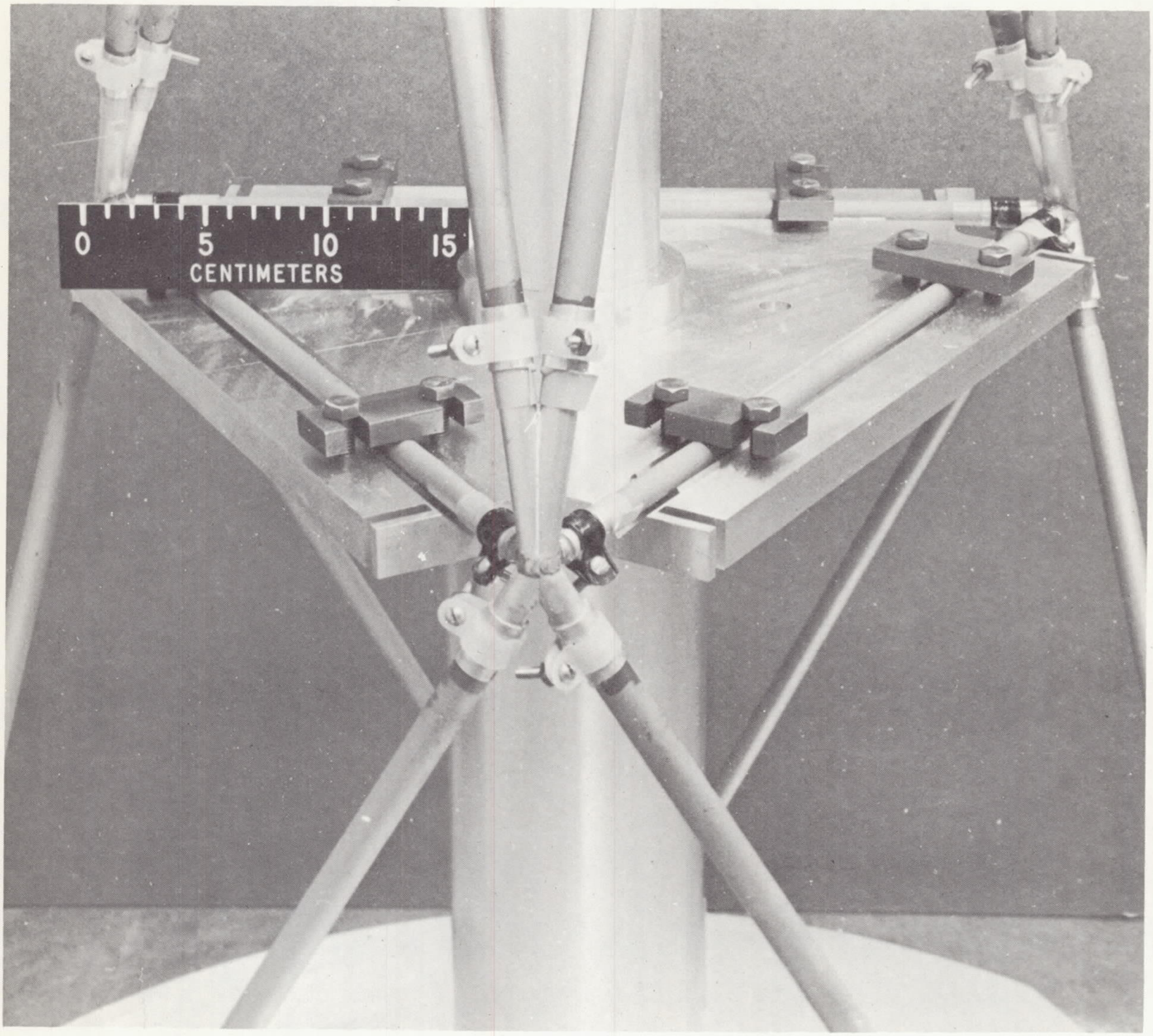
L-68-2725.1



(b) Typical vertical member joint.

Figure 17.- Continued.

L-68-2809.1



(c) Horizontal members bonded.

Figure 17.- Concluded. L-68-2811

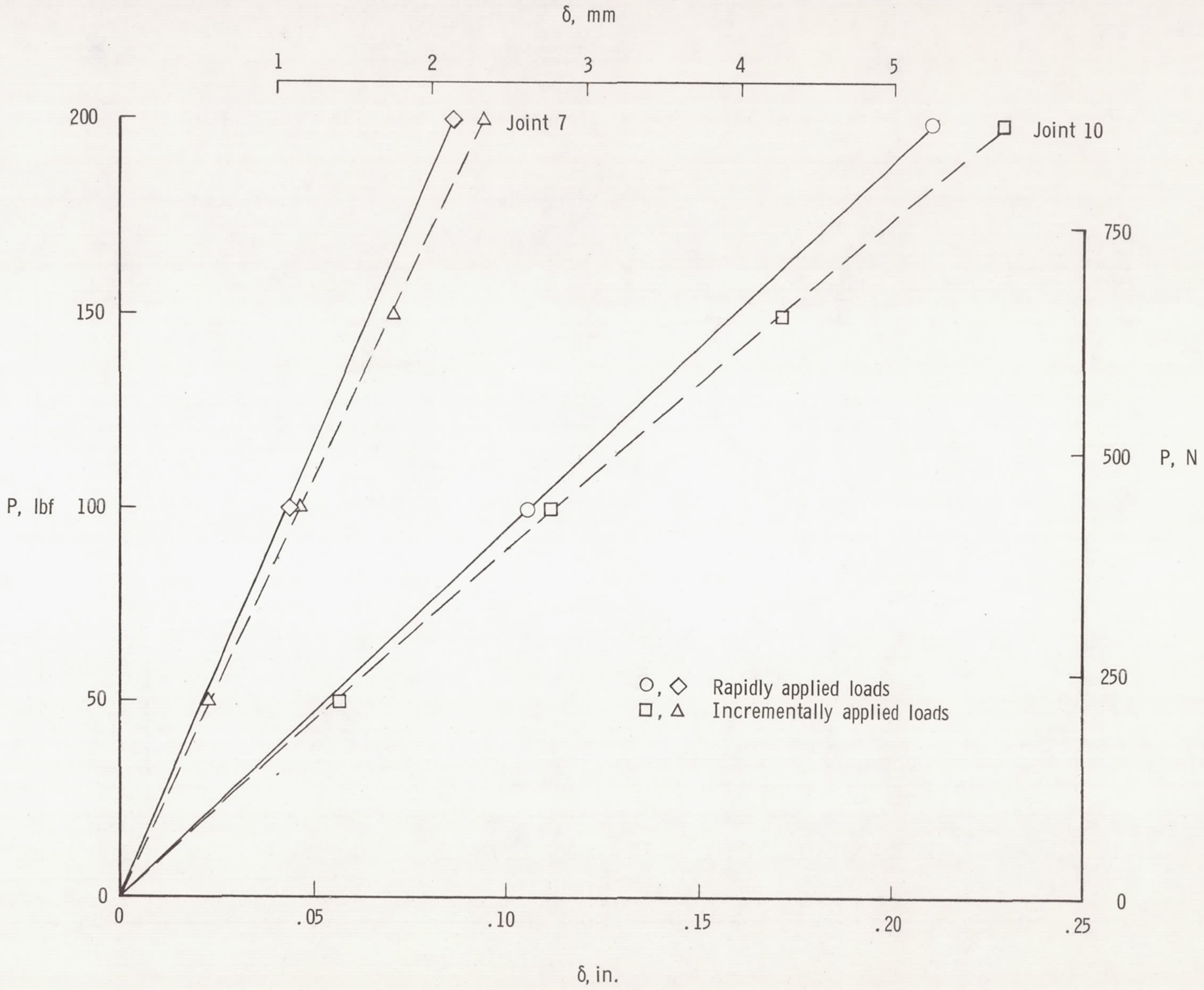


Figure 18.- Effect of method of static load application on joint deflections for bonded aluminum truss loaded in $-X_2$-direction.

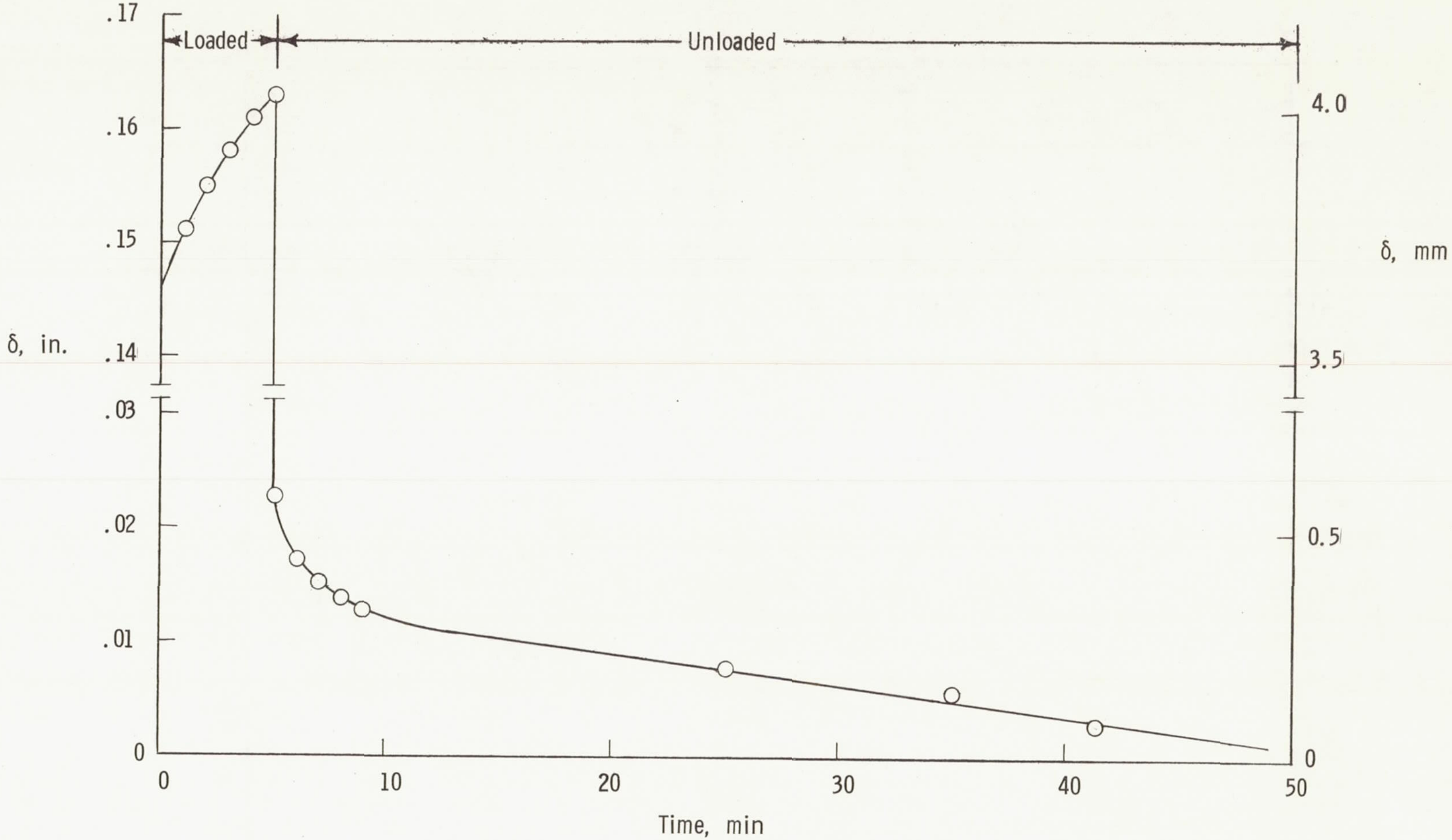


Figure 19.- Time dependence of tip (joint 10) deflection for Be-38Al truss loaded in X_1-direction. Maximum tip load, 100 lbf (445 N).

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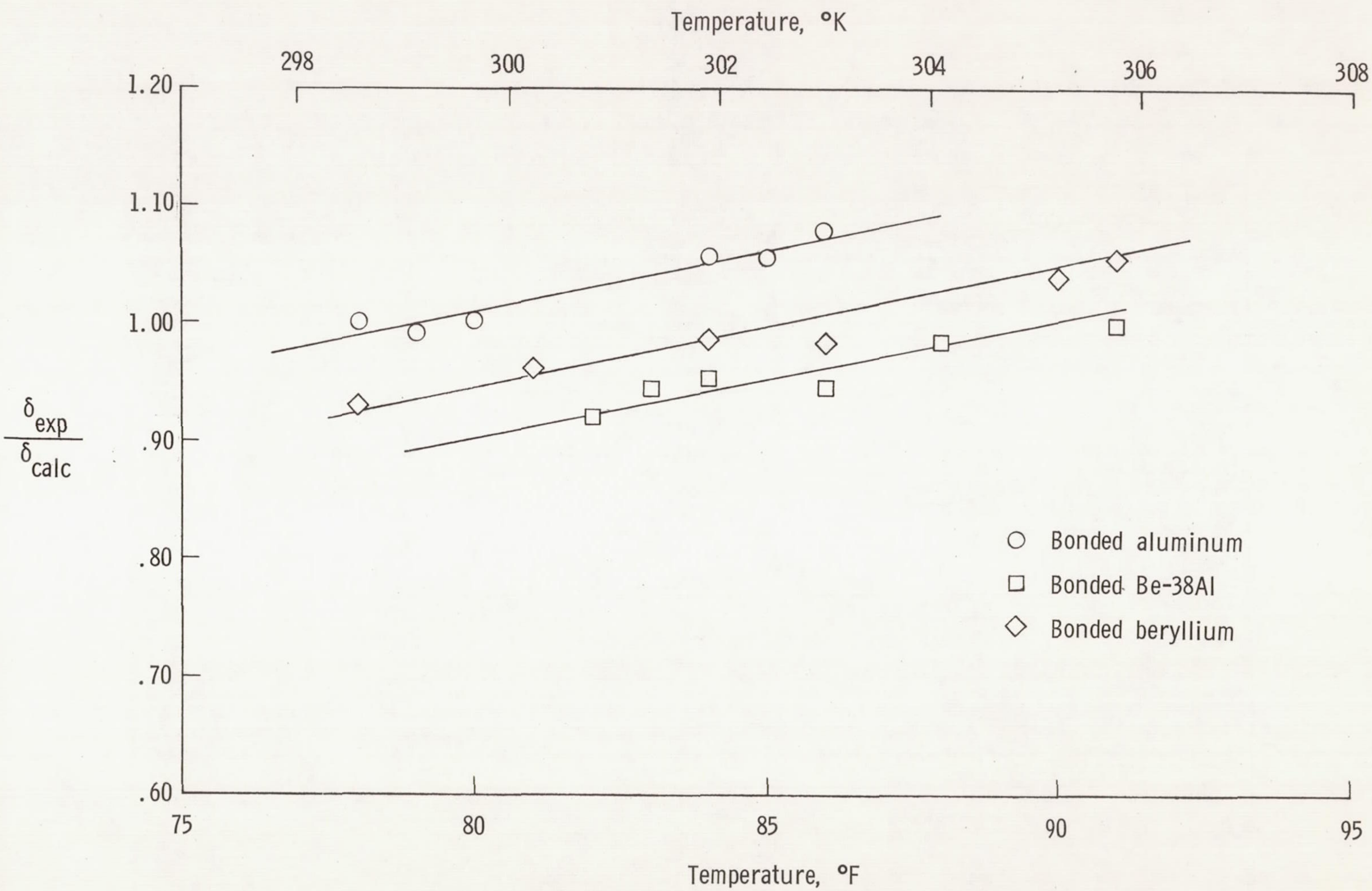

Figure 20.- Temperature dependence of normalized tip (joint 10) deflection.